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ON ELECTROMAGNETIC INDUCTION AND RELATIVE MOTION.

By S. J. Barnett.

THIS investigation originated in 1902 with an attempt to develop a method for the solution of the old problem of unipolar induction. In its best known form this problem may be stated as follows: A magnet symmetrical about its axis and rotating about this axis uniformly is touched in two points A and B not in the same equatorial plane by the ends A and B of a wire ACB. A steady current traverses the circuit thus formed. Which is the seat of the electromotive force, the wire or the magnet? That is, do the lines of magnetic induction rotate with the magnet and cut the external conductor ACB; or do the lines, like the external conductor, remain fixed while the magnet rotates through them? Faraday thought that his experiments proved the second alternative, and Pluecker shared his views, while Weber disagreed. It was first shown by S. Tolver Preston[1] that the experimental results could, as is now well known, be explained equally well on either hypothesis.

Preston went further and adduced cogent arguments in support of the first alternative, which, in a later paper,[2] he quotes Lord Rayleigh as also favoring. In the first place, Faraday had admitted that a magnet in translation carried its lines of induction with it; and Preston called attention to the fact that translation is involved in all rotation (rotation, according to his statement, being a particular case of translation); thus a large magnet in rotation is made up of many small magnets in translation, though the translation is in curved lines. In the second place if, instead of rotating the magnet, we keep the magnet fixed and rotate the conductor ACB in the opposite direction with the same speed, we obtain the same electromotive force *and its seat is in the conductor* ACB. Now

[1] S. Tolver Preston, Phil. Mag. (5), 19, 1885, p. 131.

[2] S. Tolver Preston, Phil. Mag. (5), 19, 1885, p. 215.

the *relative motion* between the parts of the system of magnet and wire is exactly the same in the two experiments, hence we should expect *ACB* to be the seat of the electromotive force when the magnet rotates and the wire remains fixed. A third argument, relating to the similarity between an electric coil and a magnet, cannot be accepted as valid, inasmuch as we know no more about the phenomena of unipolar induction in the case of an electric coil rotating without iron than we do in the case of a magnet. Both sets of phenomena can be explained equally well in the same way on either hypothesis.

Lecher[1] was not satisfied that Preston's argument was conclusive and published some highly interesting experiments, also made with closed circuits, in 1895. Although he regarded these experiments as favoring Faraday's view, they cannot be considered as establishing it. Lecher also attempted to solve the problem by electrostatic methods, but without success.

In 1902 it occurred to me that the problem could be solved by the following method. A cylindrical condenser is placed in an approximately uniform magnetic field parallel to its axis, and the magnets producing the field are rotated while the condenser is short-circuited by a wire at rest like itself. While the magnets are still rotating, the connection between the armatures of the condenser is broken; and the condenser is tested for charge after the field is annulled, or the rotation stopped, or the condenser removed. It was argued that if the lines of induction moved with the magnets the condenser would receive charges which could be computed, and that it would remain uncharged in case the lines remained fixed and the magnets moved through them. It was found later that a somewhat similar idea, discussed below, had previously occurred to Preston;[2] and in 1908 Mr. Tracy D. Waring[3] proposed an experiment essentially the same in principle as that which had occurred to me. As shown below, however, our reasoning was erroneous. Since what precedes was written, there has appeared an experimental paper on the subject by Mr. E. H. Kennard,[4] which also is based on incorrect theory.

[1] E. Lecher, Wied. Ann., 54, 1895, p. 276.

[2] S. Tolver Preston, Phil. Mag. (5), 31, 1891, p. 100.

[3] Tracy D. Waring, Trans. Am. Inst. Elec. Eng., 27, 1908, p. 1366.

[4] E. H. Kennard, Phil. Mag. (6), 23, 1912, p. 937. The inconclusive character of Mr. Kennard's work will be apparent after reading the theoretical part of this article. Using a method resembling my own, but with the iron core of the electromagnet rotating alone while the magnetizing coil remained fixed like the condenser, he thought he had proved that the lines of induction did not move with the iron, because the electrometer received no charge in his experiments. This conclusion, as shown here, does not follow. It should be pointed out also that Mr. Kennard's calculation of the effect to be expected on the moving line hypothesis assumes that on this hypothesis all the lines in his experiment would move with the iron;

Preston imagined a magnet *NS*, Fig. 1, rotating about its axis near a flat circular metal plate *K*; and concluded that if the lines of induction remained fixed the magnet would become charged by the motional electromotive forces within it, and the plate *K* by electrostatic induction, as indicated in (*a*). And he concluded that on the other hypothesis the plate would be charged as in (*b*), the magnet being uncharged except to a slight extent by induction. Preston consulted Hertz with reference to the matter; and Hertz "laid stress on the great interest attaching to

(*a*) (*b*)

Fig. 1.

the inquiry, and agreed that the conditions of test as proposed should be capable of deciding this question"; but he informed Preston that "with a normally sensitive electrometer a considerable velocity of rotation with a magnet of large size would be calculably required to produce a distinct deflection under either hypothesis." And Preston stated that "facts of this kind discouraged from trying the experiment." At the same time he expressed hope for the production in the future of a much more sensitive electrometer, with a quartz suspension.

Equally, however, with those who have tried to solve the problem by experiments on closed circuits, all who have proposed electrostatic tests to decide between the two hypotheses have, if we admit the validity of current electromagnetic theory, fallen into error; for it is not difficult to show that the total electric intensity and the electric density are in all cases the same on the two hypotheses. The error has arisen through failure to take proper account of the motional intensity in the dielectric.

For the special cylindrical condenser system considered here and imagined to be placed in a uniform magnetic field, whose direction is parallel to its axis and which is produced by a coil or magnet system in rotation, the electric field may be investigated as follows. The length of each cylinder will be considered great in comparison with the distance between

whereas it is impossible to say what fraction, on this hypothesis, would adhere to the iron and move, and what fraction would adhere to the coil and remain at rest. On account of the fact that a part of his field-producing system was at rest, instead of all being in motion, the experiments are also inconclusive as to the important matter of relative motion discussed below. To make them of value it would be necessary to make experiments on the charge taken by a short-circuited condenser, or the motional electromotive force developed in a Faraday disc, rigidly attached to the magnetizing coil of an electro-magnet whose core remains fixed while the coil rotates with the disc. The condenser experiments would be difficult; successful experiments with the disc would, apparently, be impossible.

the two cylinders, so that end effects will be negligible, and the outer cylinder may be supposed longer than the inner and closed by conductors at the ends. A fine wire may be supposed to connect the two armatures.

On the hypothesis of fixed lines it is evident that there will be no intensity, either field or motional, anywhere within the condenser system.

To obtain the field on the hypothesis of moving lines, imagine first that no motional intensity is produced in the dielectric. Then if ψ denotes the electromotive force produced in the wire by the motion of the lines of induction across it, the condenser will be charged to the voltage $V = -\psi$; and if r' and r'' denote the radii of the opposing faces of the internal and external armatures, the field intensity E, now the total intensity, at any point within the condenser and distant r from the axis will be

$$E = \frac{V}{r \log r''/r'} = -\frac{\psi}{r \log r''/r'}.$$

Now imagine that no motional intensity is produced in the wire, and consider the intensity produced by the motion of the lines of induction through the dielectric. The total intensity will be the same as if the field and wire remained fixed and the *whole* dielectric rotated in the opposite direction, and will be given by the equation[1]

$$f = e + E = \frac{\omega B}{r}\left(\frac{r''^2 - r'^2}{2 \log r''/r'}\right) = \frac{\psi}{r \log r''/r'}.$$

In the actual case the two effects will be superposed, so that the total intensity will be zero at every point. The same thing is true of the total intensity within the inner armature.

On both hypotheses, therefore, the condenser system remains uncharged.[2] The result is entirely independent of the magnitude of the dielectric constant.[3]

To establish the general proposition,[4] consider a magnet NS and any system of conductors such as a metal disc K, arranged according to Preston's dea, Fig. 2. First imagine the magnet to start into rotation

[1] S. J. Barnett, PHYS. REV., 27, 1908, p. 432. The above result follows at once by adding the motional intensity ωBr to the field intensity given by equation (11), $(K-1)/K$ being appropriately replaced by unity.

[2] That the charge is zero also follows at once from the consideration that the dielectric and short-circuiting wire together form a closed circuit, so that the electromotive force induced in the wire is just equal and opposite to that induced in the dielectric.

[3] See S. J. Barnett, Ann. der Phys., 30, 1909, p. 416.

[4] This subject, as I found after independently developing the theory for my own experiments several years ago, had been previously treated by Poincaré (L'Éclairage Électrique, 23, 1900, p. 41) and by M. Abraham (Theorie der Elektrizitaet, Vol. I., 1907, p. 418); but neither treatment seems to me satisfactory.

while the lines of induction remain fixed. Then at any point P within the magnet there is a motional electric intensity $e = [vB]$, where v denotes the velocity and B the induction at P. Owing to this intensity a transient current exists in the magnet and there is developed in and about it an electrical field which becomes steady as the motion becomes uniform. In the steady state the field intensity E at P is equal and opposite to the motional intensity e, the total intensity $f = e + E$ being zero. In the conductor K (at rest)[1] each intensity is zero. In the dielectric the field intensity E exists alone. The potential difference V, equal to the line integral of the intensity E, from any point B to any point A on the surface of the magnet along any line whatever connecting the two points is equal to the line integral ψ of e along any line ADB from A to B within the magnet. The electric density, which is proportional to the divergence of the total intensity f, is zero everywhere except at the interfaces between the conductors and the dielectric.

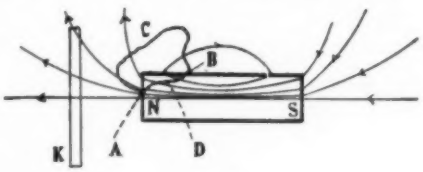


Fig. 2.

If, on the other hand, the lines of induction move as if rigidly attached to the magnet, e, E, and $f = e + E$ are all zero within the magnet; in the conductor K the total intensity f is zero, so that $E = -e$; while in the dielectric the total intensity is $f = e + E$. And this total intensity at any point is precisely the same as on the other hypothesis; for the integral of f along the line BCA is equal to the integral of e along the same line, since the integral of E vanishes along BDA and therefore along BCA, and this integral of e is equal to ψ. As A and B are any points on the magnet and ACB any line of any shape whatever connecting them, it follows that the total intensity f at any point is the same on the two hypotheses. Hence, if the *whole* dielectric is cut by the moving lines, so that the motional intensity, as well as the field intensity, acts on the whole dielectric, the electric density everywhere is exactly the same as before.

If the lines of induction neither remain at rest nor move with the full angular velocity of the magnet, the result, so far as f and the charges are concerned, is precisely the same. Though e and E will differ according to the hypothesis made, we shall always have $E = -e$, or $E + e = 0$, in the conductors, and $f = e + E$ in the dielectric, $E + e$ at any point being independent of the hypothesis.

[1] The proposition is easily demonstrated, by the application of the same method, for the case in which one or more conductors of the system K, the material dielectric, or the æther, are in motion.

Moreover, if we reject the hypothesis of the æther, as existing independently of the electromagnetic field, the result is the same. For to the electric displacement produced by the motional intensity acting on the material dielectric must be added that which would, on current theory, accompany the lines of magnetic induction if they moved in space otherwise free or filled with radiation.

Hence all attempts to solve the problem of unipolar induction by the measurement of charges or total intensities or electromotive forces are vain. For the same reason the problem cannot be solved by measuring the force upon a charged body in the field of a rotating magnet, as in an experiment proposed by Sir Oliver Lodge,[1] and suggested by Mr. Waring[2] as a means of solving this problem. It appears that the only way in which the problem can be solved electrically is to measure the two intensities separately, and how this can be done is not evident.

Much importance still attaches, however, to the proper execution of the experiment described above. For there can be no doubt, from the experiments of Faraday and many others, that if the short-circuited condenser is rotated about its axis in the fixed magnetic field it becomes charged by the motional electromotive force in the short-circuiting wire; while if the condenser and its short-circuiting wire remain fixed and the magnet or electric coil producing the field is rotated with the same speed in the opposite direction, the relative motion between the two systems is exactly the same as before, and one would expect the same charges to be developed. Indeed, the fact that the electromotive force induced in a closed circuit by relative motion between it and a magnet is independent of the one that moves is one of the considerations that led Einstein to the principle of relativity. Furthermore, a positive result would both reveal a flaw in current electro-magnetic theory and confirm Preston's idea on the seat of the electromotive force in unipolar induction. I have therefore carried to its completion the investigation begun with a different idea long ago.

After a few preliminary experiments in 1904, in which the whole condenser was short-circuited in the magnetic field and moved out after insulation to the electrometer connections, improved apparatus, in which only the outer armature moved, was tried several years later, but with inconclusive results. Work on the problem was resumed this year, and with the apparatus described below it has been possible to obtain precise and conclusive results.

Although the phenomena of unipolar induction hitherto known are

[1] Oliver Lodge, Modern Views of Electricity, 1907, Sec. 73. See also Phil. Mag. (5), 27, 1889, p. 469.

[2] Tracy D. Waring, loc. cit.

essentially the same whether a rotating magnet or a rotating electric coil produces the magnetic field,[1] it was thought worth while to investigate the behavior of both. The first experiments in the recent work were on fields without iron.

A simplified diagram of apparatus is given in Fig. 3. *C*, the coil which produced the magnetic field, was wound from about 5,000 turns of No. 14

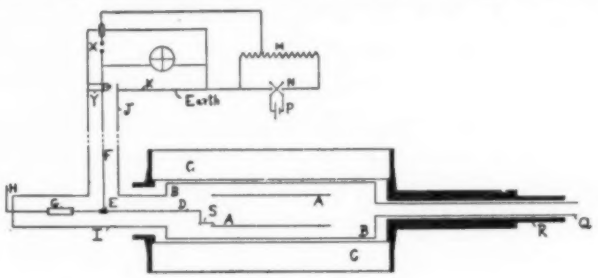


Fig. 3.

DCC copper wire on a substantial brass bobbin, to whose ends were fitted hollow axles of brass and bronze. The outer armature *B* of the (air) condenser was a brass tube 28 cm. long and 6.67 cm. in internal diameter. It was continuous with the brass tubes *Q*, *I*, and *J* and the brass lining of the wooden electrometer and key boxes *K*. The inner armature *A* was a brass tube 14.9 cm. long and 3.97 cm. in external diameter, mounted coaxially with the coil and with *B* at their common center, and insulated from *B* with two small amber blocks. To one end of *A* was attached a straight wire *S*. This wire, together with the bent wire *D*, which passed through a brass sleeve *E* in an amber support and was operated by the bent wire *H*, insulated from it by the amber block *G*, formed a key for connecting *A* by the wire *F* to the electrometer and its key *X*. The construction of this key *X* is illustrated in Fig. 4, except for a small lever

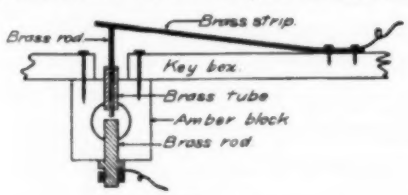


Fig. 4.

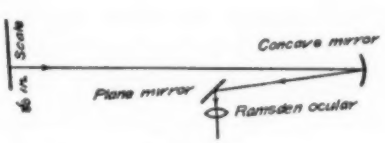


Fig. 5.

by the operation of which the key could be closed. Voltages for standardizing the apparatus were supplied by a dry cell *P* and a 10,000 ohm universal shunt box *M*, to which the cell was connected through the reversing switch *N*. The moving system was mounted in heavy brass bearings

[1] See especially O. Grotrian, Ann. der Physik, 10, 1903, p. 270.

screwed to a heavy wooden board, which was bolted to the cement floor. It was driven by an electric motor at measured speeds in the neighborhood of 20 revolutions per second and supplied with measured currents in the neighborhood of 20 amperes. The method of procedure made it necessary for the current to traverse the coil for only a few seconds in the several minutes required for each complete observation. The fixed system QBI was supported on the same base which carried the moving system. The electrometer was a modified Dolezalek instrument mounted on a wall which was absolutely free from appreciable vibration. The optical system made up a sort of Newtonian telescope, as shown in Fig. 5, and made it possible to read tenths of divisions on a one fiftieth inch scale $2\frac{1}{4}$ meters from the mirror. Sensibilities up to more than 10,000 divisions (double deflection) per volt were used. A slow stream of dried and filtered air was passed almost continuously through the tube Q, the condenser system AB, the tubes I and J, and the electrometer and key boxes K. To keep the condenser system cool during observations a rapid stream of air was ordinarily passed through the space between QBI and the coil C.

If the space between the tubes A and B were traversed by a uniform magnetic flux ϕ, and the short-circuited condenser system instead of the coil were rotated at a speed of n revolutions per second, the condenser would become charged to an electromotive force $n\phi$. The charge taken by the wire DEF would be very small in comparison with that taken by AA both in this case and in the actual case in which ϕ is not uniform. This charge does not enter into the calculations for experiments made with the key system described above, and is negligible in the later experiments made with the arrangement of keys described below.

To determine experimentally the electromotive force E to which the condenser is charged when it and the key system remain fixed while the coil rotates at the speed n revolutions per second, the procedure is as follows: The electrometer key X being closed and N open, the key DS is closed, thus connecting A and B together while the coil is in motion and the flux ϕ traverses the region between A and B. Then, in succession, contact between D and S is broken, the field is annulled and the motor switch opened while X is opened[1] and finally DS again closed.

[1] If the electrometer needle is deflected by the magnetic field of the coil or magnets, it is important that X be left closed until the needle has come to rest after the field is annulled. Otherwise a portion of the charge bound by the needle in its deflected position will be released to the insulated system as the needle approaches its zero, and there will remain a deflection which changes sign with the current. This effect, being independent of the rotation, is easily eliminated. This was done in some of the earlier work with iron when sufficient precision had been attained to detect the effect; but in all the final work, both with and without iron, the needle was allowed to come to rest before opening the key.

The reading of the electrometer is then taken. The process is repeated with the current in the coil reversed. If d denotes the double deflection of the electrometer, V the corresponding voltage, C the capacity of the system AB, and K the capacity of this system together with that of the electrometer and connections, we have

$$E = \frac{K}{C} \cdot V, \text{ or } V = \frac{C}{K} \cdot E = Ad,$$

where A is a constant. If d' denotes the double deflection corresponding to a known voltage V', we have also

$$V' = Ad'.$$

Hence, if E were equal to $n\phi$, the double deflection D to be expected would be

$$D = n\phi \cdot \frac{C}{K} \cdot \frac{d'}{V'};$$

and the immediate aim of the experiment is to determine the ratio d/D.

If the axial flux between the cylinders is not uniform, the mean value $\bar{\phi}$ throughout the length of the inner armature may be substituted for ϕ in the above formula without introducing much error, provided that ϕ does not depart greatly from uniformity and that the capacity of the system AB per unit length is nearly constant. From the dimensions and arrangement of the armatures it is evident that the second condition was satisfied in these experiments, and measurements on the magnetic field showed that the *minimum* and *maximum* values of ϕ did not differ by more than about 5 per cent. The axial flux was investigated with five test coils (set coaxially within the electric coil) ranging in diameter from a little less than the outer diameter of A to a little greater than the inner diameter of B, a properly tested Hibbert magnetic standard, and a ballistic galvanometer. Observations were made with each coil for every centimeter of the length of the condenser. The mean axial intensity thus found for the whole region occupied by the condenser was 119 gausses for a current of 1 ampere in the electric coil, the average departure from the mean given by the separate coils for the mean intensity within the cylinders described by them being about 1/6 per cent. This made $\bar{\phi}$ equal to 268×10 maxwells for a current of 1 ampere in the coil.

In order to eliminate errors arising from changes in the electrometer's sensibility and zero and from extraneous electromotive forces, the observations were made on a regular time schedule; the observations for d were repeated in inverse order; and the double deflections were obtained from the corresponding mean scale readings. If L denotes the mean

scale reading when the current traversed the coil in one direction, and R the reading when the current was opposite, $d = L - R$. The four observations necessary to obtain one value of $L - R$ ordinarily constituted one *set*.

Nine sets of rotation experiments made in the early part of the work indicated that the average value of $(L - R)/D$, with due respect to sign, was zero; but the results were very irregular, the average numerical value of $(L - R)/D$ being about one fifth.

Much of the trouble was traced to the operation of the keys X and DS, which were therefore replaced by the keys D and L, Fig. 6, of the type

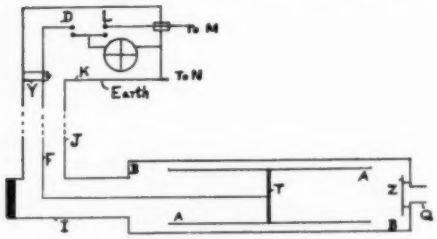


Fig. 6.

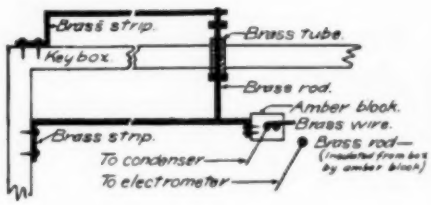


Fig. 7.

illustrated in Fig. 7, both placed in the key box. The difficulty with the old keys probably arose from the abrasion of fine particles of metal when the keys were operated, and from the presence of residual dust. Some of the discrepancies arose from the absence of perfect dryness, or constant conditions as to dryness, and some probably arose from the tremor given to the condenser and key DS by the rotation of the coil. The condenser, slightly altered, was therefore mounted directly on the wall; the amber insulators were all scraped, cleaned, and discharged in the hot gases from the flame of a bunsen burner; and the apparatus was more thoroughly washed out with filtered air. At the same time the speed was increased about 50 per cent. After these changes the discrepancies were greatly reduced, the average numerical value of $(L - R)/D$ in six sets being about 3 hundredths.

In the hope of securing still better results several changes were made. The keys were slightly improved and every effort was made to operate them with extreme regularity, the outer air stream was abolished, attempts were made to free the condenser and key box more completely from dust and to keep the air in a more nearly uniform state of dryness, and the sensitiveness of the apparatus was increased by reducing the capacity of the electrometer and connections and increasing the capacity of the condenser, and by increasing the scale distance to 3.4 meters. The scale could still be read to tenths of divisions.

The length of the outer tube *BB* of the new condenser, Fig. 6, was 28 cm. and its internal diameter 6.64 cm. The length of the inner tube *AA* was 20.0 cm. and its external diameter 5.08 cm. The capacity C_1 of this condenser was thus approximately 37.3 es. units.

The connecting wire *F*, with diameter 0.023 cm., had an effective length of 4 cm. (from the end of *AA* to the end of *BB*) in the tube *BB* and a length of 114 cm. in the tube *IJ*, with internal diameter 3.8 cm. The capacity of this system was thus approximately 11.5 es. units. The capacity of the key *D* (to a point just below the amber piece *Y*) was found by experiment to be 2.0 es. units. The capacity C_2 of the key and connecting system was thus approximately 13.5 es. units.

The capacity C_3 of the electrometer and permanent connections was determined by comparison with $C_1 + C_2 = 50.8$ es. units.

From the magnetic observations already described and additional observations made necessary by the increased length of the new condenser the mean value of ϕ, the flux through the cylindrical space between its two armatures, was found to be 169×10 maxwells for a current of 1 ampere in the coil. The maximum and minimum values of ϕ differed by about 10 per cent. of the maximum.

The coil was driven at a speed of about 32 revolutions per second, and was traversed by a current of 20 amperes.

Ten sets of observations were obtained. During the eight hours (including four hours intermission) within which the rotations occurred C_3 decreased from 60.4 to 56.5 es. units, the voltage sensibility varied from 12,900 to 12,800 divisions per volt, and *D* increased from 47 to 48 divisions. The average value of $(L - R)/D$ without respect to sign for the ten sets was 1.4 hundredths, and the average value with due respect to sign was − 0.01 hundredth.

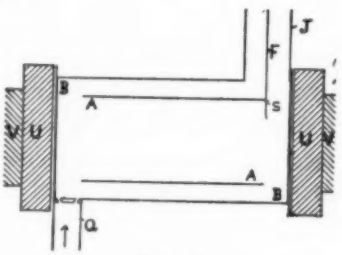


Fig. 8.

To investigate the matter when the magnetic field was produced by electromagnets the apparatus was suitably modified. Two large electromagnets *UV*, were substituted for the electric coil (Fig. 8). The cores were of steel shafting 7.5 cm. in diameter, and were capped with flat pole pieces *UU*, 12.3 cm. in diameter and 2.8 and 2.6 cm. thick, of wrought iron. The two electric coils surrounding the cores were similar, one of them being the coil *C* used in the experiments without iron. *A* was a brass cylinder 6.99 cm. in external diameter and 15.00 cm. long, *B* a brass cylinder 9.99 cm. in internal diameter and nearly 20 cm. long. The faces

of the poles UU were 20.6 cm. apart, and the whole system of cylinders, rotating and fixed, was mounted symmetrically about the center of the magnetic field. The cylinder B was covered with brass caps 12.3 cm. in diameter, and provided with a tube Q by which a stream of filtered air could be sent through the condenser and electrometer systems. The electromagnets were driven by an electric motor at about 32 revolutions per second. In the earlier part of the work the condenser system was supported on the same base boards with the electromagnets, and the key system consisted of the same key X used in the experiments without iron together with another key constructed on the same principle as DS in those experiments and similarly located; but experience of the sort already referred to in the case of the experiments without iron led to changes quite similar to the changes made in those experiments. The calibrating apparatus and the method of observation were the same as in the experiments without iron.

The mean value of the axial magnetic flux in the space between A and B was determined by ballistic observations as in the former experiments, but with two sets of test coils in the shape of two uniformly wound solenoids with the same number of turns per cm., one with diameter slightly less than the external diameter of A, the other with diameter slightly greater than the internal diameter of B, and each somewhat longer than A. Each solenoid was provided with four pairs of leads—two leads with 20 turns between them, two with 40, two with 60, and two with 68, making four test coils for each solenoid, all with a common center. Each solenoid in turn was placed symmetrically in the magnetic field and the flux through each of its four coils determined when a current of 10.0 amperes traversed the electric coils of the magnets. By plotting the difference between the fluxes for the corresponding coils as a function of the number of turns, obtaining from the curve the flux corresponding to the number 64.9, the number of turns in 15 cm., the length of A, and multiplying by the ratio of the right cross-section of the space between A and B to the right cross-section of the space between the mean circumferences of the solenoids, the value of $\bar{\phi}$ for a current of 10 amperes in the electric coils was found to be about 289×100 maxwells. Table I.

TABLE I.

Number of Turns in Each Coil.	20	40	60	68
Magnetic flux in maxwells × 10,000.....	55	122	189	220

gives the relation between differential fluxes and turns for the solenoids

and shows that, as in the previous experiments, the flux ϕ is not far from uniform. Magnetic tests for currents above 10 amperes were carried out, but the comparatively small increase in flux (20 per cent. in changing from 9 to 16 amperes) did not appear to justify the large additional amount of heat generated in the coils; so that the experiments on rotation were always carried out with currents in the neighborhood of 10 amperes. Except in the early experiments, the currents were always somewhat *greater* than 10 amperes.

The earliest experiments were still less precise than the corresponding experiments without iron, but gave, like them a null effect. With the condenser on the wall and the key system improved, but not in its final state, the average magnitude of $(L - R)/D$ in 14 sets was reduced to about 5 hundredths. A slight further reduction to about 4 hundredths in 23 sets was made after the readjustment of the electrometer.

Finally, after still further attempts to improve conditions, 12 sets were obtained in which the average magnitude of $(L - R)/D$ was reduced to 1.7 hundredths, the average value with due respect to sign being + 1.2 hundredths. During nearly all of the time in which the last five sets were obtained the electrometer was in unusually stable condition; before these sets were begun the clamp of one of the keys had been improved; and throughout the five sets the keys were operated with even greater care than formerly. For these sets the average magnitude of $(L - R)/D$ was 0.8 hundredth, and its value with due respect to sign was + 0.6 hundredth. About an hour after the last set was obtained rotations were again started; but conditions had become poor, giving large discrepancies, and observations were discontinued.

In the interval of four hours devoted to these 12 sets the voltage sensibility of the electrometer ranged from 12,700 to 12,600 divisions per volt; the capacity C_3 of the electrometer decreased from 54.4 to 50.3 es. units; and D changed from 28 divisions to 29 divisions.

The capacity of the condenser AB was approximately 21.0 es. units; the capacity of the wire (about 106 cm. in length, 0.023 cm. in diameter) and tube $SFY - J$ was about 10.4 es. units; and that of the key DY, about 2.0 es. units, (Figs. 6 and 8). C_2, the capacity of the key and connecting system, was thus approximately 12.4 es. units. C_3 was again obtained by comparison with $C_1 + C_2$.

The investigation leads conclusively to the result that the condenser system, when it remains at rest and the system producing the field rotates, receives not more than a minute fraction of the charge it would receive for the same relative motion if the system producing the field remained at rest. Within the limits of error of the experiments—about

1.4 per cent. in the experiments without iron, and about 1 per cent. in the experiments with iron—the fraction is zero.

For the construction of most of the special apparatus used in this investigation I am indebted to Mr. Tudor T. Hall, mechanician at the Tulane University of Louisiana, and Mr. Arthur Freund, mechanician in this laboratory. I am indebted to Mrs. Barnett for important assistance throughout the experimental part of the work.

The Physical Laboratory,
The Ohio State University,
July and October, 1912.

ON ELECTROSTATIC SCREENING BY THIN SILVER FILMS.

By Miss Shirley Hyatt.

THE original purpose of this investigation was to determine the thickness of a metallic film necessary to screen an electroscope within a closed, hollow conductor from induction by outside charges. It had been observed that a glass vessel covered with a thin silver film was transparent to induction from outside charges, and the present work was undertaken to determine the limiting thickness through which the effect could be observed.

The first part of this work was done in the year 1907–08. All the films used in the investigation were chemically deposited upon glass plates by the Rochelle salts method, as described in Mann's Optics. A tin can with small windows cut in opposite sides was first used as a hollow conductor. The windows were screened by wire gauze, which was soldered to the can. A gold leaf electroscope was placed in the can with its charging disc about two millimeters below the cover of the can. A hole a little larger in circumference than the disc of the electroscope was cut in the cover of the can. Over this hole the silvered plate was placed, the film side resting on the tin, thus making a closed, hollow conductor of the can. The leaves of the electroscope were observed by means of a microscope through the screened windows of the can.

A short copper cylinder of about the same circumference as the electroscope disc was provided with an insulating handle, and was connected by a copper wire to one terminal of an electric machine. This cylinder was usually placed upon the glass plate immediately above the electroscope disc, and was then charged by means of the electric machine. Any deflection of the electroscope leaves due to induction by this charge was then observed.

The films were at first deposited upon window glass and were very irregular in thickness and no attempt was made to measure their thickness. When the thinner films were used a very apparent movement of the electroscope leaves was observed. The thicker films were opaque to the induction. One film, in particular, aroused interest. The silver deposit was uneven, being very heavy at one edge and shading off very thin at the opposite edge. When the charged cylinder was placed over the thin part the electroscope was plainly affected, and as it was moved

along toward the thicker edge a position was found where the film was opaque to the induction.

Pieces of plate glass 5 mm. thick and 10 cm. square were then procured and silvered. Great difficulty was experienced in preparing smooth, uniform films thin enough to show induction. After the greatest precautions had been taken in cleaning the plates and in preparing the solutions most of the films would be streaked or spotted. Most of the great number prepared were not worthy of measurement, either on account of irregularities in thickness or because they were not near the limiting thickness which was to be determined.

The thickness of the films was determined by weighing. After the electrical and optical transparency of the film had been observed, its dimensions were measured and the silvered plate was counterbalanced by a similar plate and weighed on a sensitive balance. The silver film was then wiped off by a piece of chamois leather or a cotton towel and the plate was reweighed. A two mg. weight and a one mg. weight were the only pieces ever changed in the weighing.

The optical transparency of the films was determined by measuring the percentage of transmitted light of wave-length about 600$\mu\mu$ by means of a Lummer-Brodhun spectral photometer. Readings were taken through various parts of the film and a mean value used.

The following table gives the results of this work in 1907–08. The films numbered 1 to 9, inclusive, were made on glass plates from old photographic plates, the others were made on plate glass. The results are not uniform and there are apparent contradictions, especially in the transparency to light, as in plates 1, 2, and 6. It would seem, however, that at a thickness of about 40 to 50$\mu\mu$ the silver film becomes opaque to electrostatic induction, while plates thinner than this allow induction to take place through them.

Plate.	Character.	Wt. in Mg.	Area in cm^2.	Thickness in $\mu\mu$.	Electric Transparency.	Light Transparency, Per Cent.
1	Uniform	2.7	78	33	Transparent	25
2	Uneven	2.84	82	33	Transparent	53
3	Uniform	6.2	66.5	88	Opaque	3.4
4	Uniform	4.48	77.2	55	Transparent	22
5	Uniform				Opaque	9.4
6	Uniform	5.49	82.8	63	Opaque	33
7	Uniform	3.9	77.9	47	Opaque	17.5
8	Uniform	4.5	78.3	55	Opaque	
9	Uniform	2	78.3	24.3	Transparent	
12	Uniform	2.02	53.6	36	Very trans.	27
13	Very thin				Very trans.	50
14	Uniform	1.9	78.3	23	Opaque	

This investigation was again taken up in 1912 with some variations in the apparatus used. The films were deposited as before upon pieces of plate glass. A wooden box covered with tin foil was used as the hollow conductor. The front of the box was open, the electroscope being shielded by a flap of tin foil hanging from the top about half way down. The lower part was used as a window through which the electroscope could be observed. An aluminium leaf electroscope provided with a scale for reading the deflection of the leaf, and mounted in a tin box with a glass front, was placed in the wooden box with its charging disc centrally below a square opening cut in the top of the box. The top of the electroscope disc was about 5 mm. below the upper surface of the box. The silvered glass plate was then laid with its silver film in contact with the tinfoil over the opening in the top of the box. A copper disc of about the same diameter as the electroscope disc and provided with an insulating handle was used to induce the charge in the electroscope.

The charge was not taken direct from the electric machine, as in the earlier work. Instead, a Leyden jar was charged from the machine and this was connected through a Braun electrometer to the copper disc. By this means, the voltage of the disc could be read up to 3,500 volts.

The thickness of the films was determined as before, a 2 mg. weight being the only one changed during the weighing.

The data determined from these observations are given in the following table.

Plate.	Character.	Wt. in Mg.	Area cm².	Thickness in $\mu\mu$.	Voltage of Disc.	Electric Transparency.
I.	Uniform.	4.3	91.9	44.7	3,500+	Opaque.
II	Uniform.	2.1	91	22	3,500	1 scale division.
III.	Fairly uniform.	1.7	64	25	1,600	22 scale division.
IV.[1]	Very thin.	4.03	93	41.3(?)		Very transparent.
V.	Thin, uniform.	1.63	89	17.4	1,000	Very transparent.
VI.	Uniform.	1.62	85.5	18.1		Transparent.
VII.	Uniform.	1.93	92.6	19.8		Transparent.
VIII.	Uniform.	3.36	94	33.7	3,500+	Opaque.

From this series of plates it would seem that the limiting thickness was about 30$\mu\mu$, but the voltages used were much lower than in the former series when the inducing cylinder was connected directly with the electric machine. The results of the two series seemed to indicate, however, that at some limiting thickness of from 30 to 50$\mu\mu$ a silver film when used as part of a hollow conductor becomes opaque to electrostatic induction from outside.

[1] No. IV. seems to give discordant results. It looks to be one of the thinnest films made, buts its weight was apparently over 4 mg.

During these experiments it was observed that if the electroscope within the hollow conductor was previously charged it became much more sensitive to induction from without. Another important difference was observed between the charged and the uncharged electroscope. If a very thin silver film was placed over the uncharged electroscope and the charged disc was placed upon the glass plate upon which the film was deposited (thus being insulated from the film by the 5 mm. thick glass plate) the leaf of the electroscope would fly out to a large deflection, then would gradually fall to a lower position which it would hold. When the charged disc was removed from the plate the leaf was again deflected and then fell to its zero position. If the electroscope had been previously charged this second deflection was in the opposite direction from the first, indicating that it was due to an inducing charge of the opposite sign.

This seemed to indicate that the film, which was in the beginning transparent to outside induction, became a screen only after a charge opposite in sign to the charge on the copper disc had gathered upon it. When the charged disc was removed this induced charge upon the film then induced an opposite charge upon the electroscope disc which remained until the charge on the film was again distributed over the hollow conductor. That is, the screening effect of the film seemed to depend not upon its thickness, but upon its conductivity.

The first measurement of the specific conductivity of thin films was made by Miss Isabelle Stone in 1898.[1] Miss Stone used silver films prepared in the same manner as those used in this work. She found that for thin films the observed electrical resistance is very much greater than that calculated from their weight, density and dimensions. She found that the ratio of the observed to the calculated resistance was large when the thickness was less than $250\mu\mu$, and was tremendously large when less than about $20\mu\mu$.

Professor J. Patterson[2] also investigated the conductivity of platinum, bismuth and silver films deposited in vacuo by the cathode discharge. He found that for thin films the specific resistance is several times as great as the specific resistance of the metal from which they are deposited. He was unable to prepare very thin silver films, but he found that for platinum films the limiting thickness at which the specific resistance began to increase greatly was between $7.7\mu\mu$ and $4.6\mu\mu$. Following J. J. Thomson's theory, he regards this change in specific resistance as depending upon the ratio of the thickness of the film to the mean free path of the electrons in the metal.

[1] PHYSICAL REVIEW, Vol. VI., p. 1, 1898.
[2] Phil. Mag., VI., Vol. IV., p. 652.

Vincent[1] used the resistance of silver films to determine the radius of molecular attraction. He gave as his conclusions, "A film of silver which is greater than $50\mu\mu$ in thickness is composed of a homogeneous layer of constant specific resistance, which is between two layers of less but fixed conductivity whose resistance is constant." He established a formula for calculating the specific resistance of thin metallic films; thus

$$\frac{1}{r} = -A + ce,$$

where r is the resistance, c the specific resistance, which is constant, and e the thickness of the film. This formula seemed to hold for films having a greater thickness than $50\mu\mu$, which thickness he regarded as the sum of the two transition layers on opposite sides of the film, thus making the radius of molecular attraction $25\mu\mu$. Patterson, using Vincent's data in a formula proposed by J. J. Thomson, obtained $60\mu\mu$ as the mean free path of the electrons, or the thickness at which the specific resistance should begin to change.

Moreau[2] in making investigations on the Hall effect in silver films obtained observed values which were comparable with the theoretical values derived from Vincent's formula, thus confirming Vincent's work. Quincke,[3] who made the first direct measurements upon the radius of molecular attraction in silver, found this magnitude to be greater than $50\mu\mu$, while C. W. Chamberlain[4] using a similar method found a value of $1.5\mu\mu$.

While the estimates of the radius of molecular attraction vary greatly, the investigations upon the conductivity of thin films all indicate a great change in specific resistance at about the thickness where the films used in this investigation became opaque to electrostatic induction. Accordingly, a number of observations were made with plates of poor conducting material placed over the opening in the hollow conductor above the electroscope, and with metal plates insulated by mica or glass and connected to the hollow conductor or to the earth through high resistance. It was found that a glass plate with no silver film on it acted like a very thin film, but much more slowly. The following table gives the electroscope deflections induced through film V and through a clean glass plate of the same thickness as the one upon which the film was deposited. The figures in the time columns give the time elapsed after the charged disc was placed upon the plate or removed from it. In Fig. 1 of Plot I., the

[1] Annales de Chimie et de Physique (7), XIX., 421, 1900.
[2] Journal de Physique (3), X., 478, 1901.
[3] Pogg. Ann., Bd. 137, p. 402, 1869.
[4] PHYSICAL REVIEW, XXXI., p. 170, 1910.

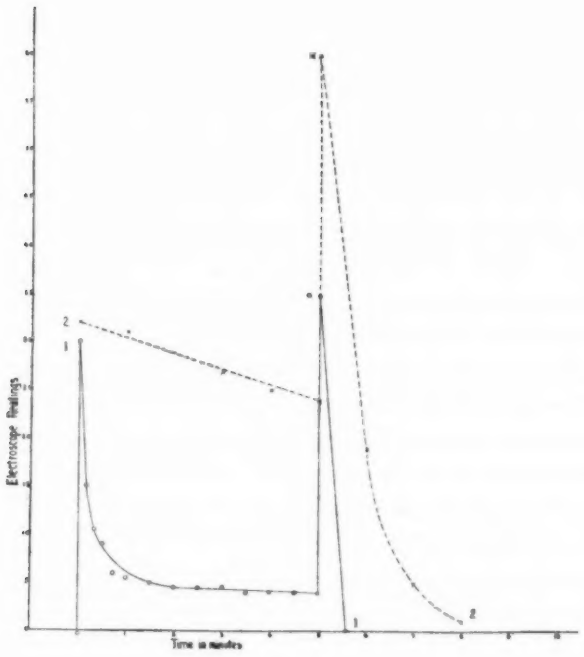


Fig. 1.

Silver Film F; Thickness 17.4 $\mu\mu$.			Glass Plate.		
Time in Sec.	Scale Divisions.	Charge in Volts.	Time in Min.	Scale Divisions.	Charge in Volts.
0	30	1000	0	32	1000
10	15		1	31	980
20	11		2	29	950
30	8		3	27	930
50	7		4	25	910
60	6		5	24	900
90	5	900	Charge removed.		
120	4	880	0	60	950
150	4	840	1	18	
180	4		2	5	
210	3		3	1	
240	3				
270	3				
300	3	800			
Charge removed.					
0	35	860			
30	0				

deflection of the electroscope leaf is plotted against the time elapsed after the charged disc was placed upon the glass plate of the film, and after it was removed. It will be seen from this that the shielding charge

gathered upon the film almost entirely in one minute, after which time the deflection remained constant until the inducing charge was removed. When, after five minutes, the inducing charge was removed, the instantaneous deflection of the electroscope leaf is shown at point *a* on the plot.

Fig. 2 gives a comparison plot for the unsilvered glass plate. In this case the shielding charge gathered much more slowly, so that in five minutes the electroscope deflection fell only from 32 to 24 scale divisions. When the inducing charge was removed, the instantaneous deflection

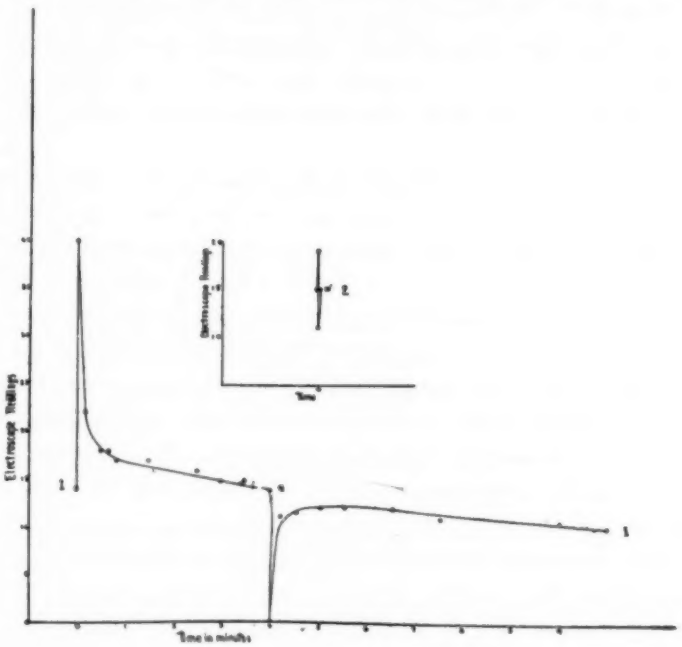


Fig. 2.

was much greater than in the case of the film, showing that the induced charge was dissipated more slowly.

Similar observations were taken for a number of films, but all behaved in the same manner. When the film was insulated from the hollow conductor, either by placing the glass side next to the box, or by placing a sheet of glass or mica between it and the box, the shielding charge did not gather at all, or gathered very slowly. When the inducing charge was placed above the film the electroscope was deflected, and when the inducing charge was removed the electroscope leaf fell to its zero position. This was true whether the electroscope was charged or not. It was equally true when metal plates of different thicknesses were placed over the opening in the hollow conductor and joined to it or to the earth by

a very poor conductor. In this case, the thickness of the metal screen had no appreciable effect, a copper slab about 1 cm. thick acting like a thin film under the same conditions.

A large number of experiments of this kind were made. A hollow conductor was made from a tightly soldered tin can with wire gauze windows. A hole was cut in the top, and the electroscope was placed with its disc just below this opening. A copper plate much larger than the opening in the tin can was laid over this opening and insulated from the can by a very thin disc of mica. When the charged disc was moved toward or away from this plate the electroscope was plainly deflected. When the electroscope was charged, these deflections were in opposite directions when the charged disc was approaching and when it was receding from the plate.

A copper wire was then soldered to the copper plate. When this wire was held in the hand the electroscope was plainly deflected by moving the charged disc above the plate. The same was true when the wire was wound tightly about a gas pipe or about a steam radiator in the room, but when the wire was soldered to the gas pipe no deflection could be observed. The hand could be pressed upon the copper plate and induction would still take place through it; but if one finger were placed upon the plate and another finger of the same hand upon the hollow conductor beside the plate, no induction could be observed. No induction could be observed when the plate was connected to the tin can through soldered contacts and 100,000 ohms resistance, but the induction was large when the two were connected through a hemp string or when the copper plate was insulated by filter paper. If the paper were wet, no induction could be observed. Induction could plainly be observed through a sheet of tinfoil which was spread over the opening in the can and was held down only by its own weight, and it was even observed through a sheet of tinfoil which was soldered to the can at its four corners.

Since the screening effect of the silver films seemed to depend only on their conductivity, and not at all upon their thickness, a thick film which served as a perfect screen when it was laid on the tinfoil covered box, was cut into squares by using a sharp knife and cutting through to the glass along a ruler laid on the film, thus making narrow slits across which the charge would have to leak in order to gather on the film. In this condition it became very transparent, and acted like a very thin film.

A piece of tinfoil pasted on plate glass allowed some induction to take place through it when laid with its foil side on the tinfoil covered box, but this induction was only instantaneous, and the electroscope would

at once return to zero. If the electroscope was charged, a sudden deflection and an instantaneous dropping back to the former position on the scale was observed when the charged disc was placed on the glass above it. When the disc was removed, the deflection was in the opposite direction, and the return to the original position was again instantaneous. The tinfoil was then cut into squares, as in the case of the silver film already mentioned. It now acted like a thin silver film.

Fig. 1, Plot II., shows the electroscope deflection at successive intervals of time after the charged disc was placed above the cut tinfoil, and after it was removed. The electroscope was charged so that its leaf stood at 14 of the scale before the charged disc was brought near. When this disc was placed on the glass above the tinfoil, the leaf was deflected at once to 40. It then fell back, rapidly at first and more slowly later until after 4 minutes it again stood at 14. The charged disc was then suddenly removed. The electroscope leaf at once fell to zero of the scale and then came back rapidly to near 14 again, after which it held its position until its charge leaked off.

Fig. 2 of Plot II. shows the induction through the same tinfoil sheet before it was cut into squares. In this case the deflection each way was much less, and its fall back to its zero position was almost instantaneous.

These experiments seem to make it very probable that electric induction does take place readily through metals until the inducing charge is counterbalanced by a charge of the opposite kind which is induced upon that surface of the metal which is nearest to it. The assumption that the apparent induction through metals is due to a charge like the inducing charge which is driven to that part of the metal screen which is farthest from the inducing charge would seem to be contradicted by the phenomena observed in thin films. In this case, if opposite charges are induced upon the two surfaces of the film, these charges are very close together,—less than 1/10 a wave-length of light apart, in many cases. The electroscope disc upon which the charge was induced was, in these experiments, about 5 mm. distant from the film, or more than 100,000 times the distance between the two charges. If both could act upon the disc, their mutual effect would be zero. If only the one on the lower side of the film could act, the other being screened by the film, then the film became a screen when this lower charge had leaked away. There would accordingly have been no inducing charge left upon the lower face of the film when the charged disc was removed from above it, and the charge upon the upper surface could have produced no effect upon the electroscope until it had passed through to the inner surface of the film. But according to all theories of hollow conductors, an electric charge placed

upon the exterior surface will not penetrate to the interior surface unless there is a charge of the opposite sign within the hollow conductor.

Also, from J. J. Thomson's theory, since the thickness of these films was much less than the mean free path of the electrons within the metal, the charge could not have gathered upon either surface, but must have been distributed throughout the film. Two opposite charges upon the same film would in such a case be impossible.

This work was carried on in the Physical Laboratory of Stanford University, under the supervision of Professor Sanford.

STANFORD UNIVERSITY,
June, 1912.

NOTES ON THE ELASTIC PECULIARITIES OF PLATINUM-IRIDIUM WIRES.

By L. P. Sieg.

1. *Introduction.*—The interesting elastic properties of platinum wires alloyed with iridium have been discussed in several papers.[1] The hope has been expressed at several times during the work of determining the equations that would represent the elastic action of these wires. The only matter that seemed to stand in the way of one's obtaining such definite mathematical relations was the lack of a sufficient variety of data. During the past two years many additional observations have been made on these wires, but in spite of the additional information gained by these experiments, no successful mathematical theory has been reached. However, it was thought best to present some of the more interesting elastic peculiarities of these alloys. Many of these results are very suggestive in the general subject of elasticity.

2. *Test of Hooke's Law.*—For many of the phenomena connected with these wires the former papers should be consulted. Only one result will be repeated here, as it is of importance in this section of the work. The wires which are used as the suspensions for torsion pendulums are alloys of platinum with various percentages of iridium. Most of the results are on a forty per cent. alloy, and it will be undersood that this particular alloy is meant unless the contrary is stated.

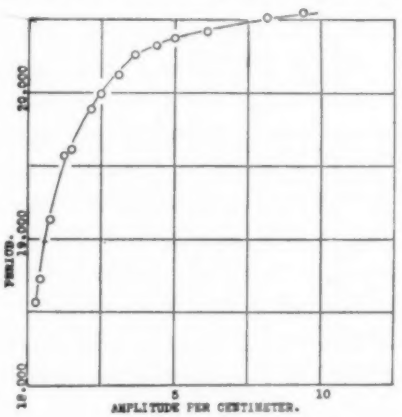


Fig. 1.

The pendulum is twisted from the zero position to an amplitude of about 12° per cm. of length, and its period is determined as a function of its amplitude.[2] In Fig. 1 is shown a curve representing a typical results of such an experiment. For the special methods of observation, timing,

[1] For references to former papers see Phys. Rev., XXXI., 1910, p. 421.

[2] In former papers the word "amplitude" was used to represent the complete range of vibration. In the present paper it is used in its ordinary sense as referring to the angular displacement from the center.

etc., the former papers should be consulted. One of the first thoughts that occur to one in observing this curve is that perhaps here is a case where Hooke's law does not hold. The large period which stays almost constant down to an amplitude of about 5° per cm. of length seems to correspond to a constant and small restoring torque in the wire. Down to this place on the curve the conditions seem to be nearly normal. However, below this amplitude the period falls off rapidly, indicating thereby the possibility of an increase in the restoring couple per degree of twist. Some experiments were made to test this point. In the experiments recorded in some of the former papers[1] static determinations had verified the fact that Hooke's Law holds almost exactly up to the maximum twist. So from static determinations there is no evidence of any change in the torsional moment per unit angle of twist of the wire with angle of twist. It seemed quite desirable to make here a similar test, only in this case to have the wire in actual vibration while the test is being made. There seemed to be the possibility of an elastic after effect which in a static determination would disappear too rapidly for observation. After trying several plans to get at the method of measuring Hooke's Law kinetically, the following was adopted. In Fig. 2 the wire under test, w_1, is represented as being joined to a steel wire, w_2, by means of a light brass coupling, c. Two mirrors were used: m_1 attached to the lower end of the wire, w_1, and m_2 fastened by means of a light rod, R, virtually to the lower end of w_2. The mirrors were placed together so that one beam of light could strike the two and the images be focused simultaneously on a circular graduated scale. Suppose that when the system is stationary the resting point of the spot of light from m_1 is represented by x_1, and of that from m_2 by y_1. Suppose now the system is twisted. Let the new reading of the spot from m_1 be x_2, and from m_2 be y_2. The twist of the wire w_1 is represented by $x_2 - x_1$ while the twist of w_2 is represented by $(y_2 - y_1) - (x_2 - x_1)$. With this apparatus we are prepared to test Hooke's Law both statically and kinetically, provided we assume that the above law holds for the steel wire. This latter assumption seems reasonably justified, at least within the experimental possibilities of this apparatus. For static determinations the lower weight was twisted, after the zero positions of m_1 and m_2 had been determined, was clamped at various degrees of twist, and the several corresponding readings of m_1 and m_2 were determined. In the kinetic observations there were two plans used. In the first place

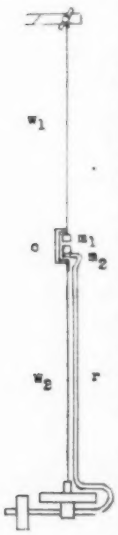


Fig. 2.

[1] Loc. cit.

the system was vibrated and the simultaneous turning points of the spots of light from m_1 and m_2 were noted by two observers. These observations gave information of course at the turning points only, and in a way this experiment is not essentially different from the former static ones, for the wires were at the moments of observation, momentarily at rest. In order to test the action during the actual vibration of the wire, recourse was had to photography. The camera was focused on a portion of the scale where previous observation had located the simultaneous appearance of the two spots of light. The rest points of m_1 and m_2 were of course first determined, then during the actual vibration an instantaneous exposure of the two spots of light was made. Exposures were taken at several different parts of the scale, corresponding to various degrees of twist, and of parts of the vibration. The results of these observations, which to save space are not presented here, indicate clearly that within the accuracy of the method used, the restoring torque is at all times, whether the wire is in motion or not, proportional to the angular twist. So one must look elsewhere than to the failure of Hooke's Law for the explanation of the curve in Fig. 1.

3. *Test for Angular Harmonic Motion.*—An indirect test of the question raised in section 2 above seemed possible. That is, if Hooke's Law fails, then perhaps the motion of the vibration is not angular harmonic. It seemed worth while then to test this point. At first an attempt was made to arrange below the wire under test a second torsion pendulum having a steel suspension. The plan was to use two mirrors, similar to the arrangement in Fig. 2, to adjust to equality the periods and amplitudes of the two pendulums, and then to set the two going simultaneously from the same point of rest. It was hoped that if the vibration of the platinum-iridium wire was not truly angular harmonic, that the two spots of light, while starting together, and reaching possibly the extreme amplitudes at the same time, would not at the other points of the scale be together. It was found impossible to adjust the two pendulums together, for while the steel one was practically isochronous, the other one, as indicated in Fig. 1, changed enormously in its period with varying amplitude. The method was then abandoned on account of the many practical difficulties encountered. The next method, and the one that seems to have been successful, was to get a trace of the vibration on photographic paper mounted on the revolving drum of a chronograph. As the width of the chronograph cylinder was only 25 cm. it was necessary to have a small vibration. This in no way caused any difficulty, for the length of the wire was reduced to such an extent that the same twist per unit length as in former experiments was possible, even with the very

limited amplitude. A vertical slit of light was focused on the drum of the chronograph in front of which was a thin horizontal slit. This gave on the drum a very fine point of light, and this arrangement had the additional advantage over the focusing of a point of light in that small vertical oscillations of the vibrating pendulum were not recorded. Thus a perfectly smooth curve was obtained. The room was darkened, the drum covered with the photographic paper, and the pendulum and the drum were started. When all was steady a cardboard stop was removed from the front of the horizontal slit, and light was admitted until about fifteen or twenty semi-vibrations had taken place. The paper was developed, and when carefully dried was ready for measurements. The paper was of an excellent heavy stock and if there was any shrinking it was thought that it would not affect any one measurement more than any others. Several such records were obtained. Now before final measurements on these curves can be made, two reductions must be carried out. The first is the reduction of the tangent of the angle of twist to the angle, for the drum was tangent to the circular scale. The next reduction was a little more difficult to make, and also a little more uncertain. Those who have read the former papers will recall that the logarithmic decrement of the vibration of these wires is not only variable, but is also very large. So the traces on the photographic paper were similar to such a highly damped vibration as that represented in Fig. 3. This figure is, however, much exaggerated. In the first place along the central line AB, each segment such as CD is divided into n equal divisions. In the present work n was made equal to ten. Ordinates were erected at each of these divisions. Let the ordinates erected at the middle points of the segments be represented in length by a_1, a_2, a_3, etc. The times represented by the distances between these small divisions are each taken as unity. Then in Fig. 3, the times at which the amplitudes a_1, a_2, a_3, etc., occur are 3, 9, 15, 21, etc., units. Then the amplitude of any of the median ordinates a_1, a_2, a_3, etc., is supposed given by the expression

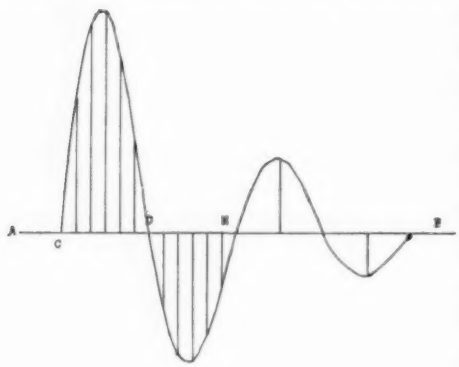


Fig. 3.

$$a_0 = a_t e^{mt},$$

where a_t is any measured median ordinate, a_0 the first measured median

ordinate, t the time elapsed in the arbitrary units, while m in this weir is a variable function of the time elapsed, and not a constant as it is in most wires. The value of m as a function of the vibration number is platted in Fig. 4. After m is determined, any other than a median ordinate is measured and reduced to what it would be were there no damping. To illustrate briefly the general method, a special case from Fig. 3 will be taken. Suppose we take the measurement of the ordinate at H. To get its adjusted length it is adjusted by multiplying by e^{11m}; the number 11 representing the number of units of time elapsed since the beginning. The value of m is taken from the curve in Fig. 4 at the time interval 11. This is found to be about .00410. After all these ordinates are measured and adjusted (and there were over ninety of them to each curve) to what would have been their magnitude had there been no damping, all the corresponding ordinates were averaged. Lastly these were compared with multiples of the natural sines of the corresponding angles. The constant multiplier of sin θ was so taken that the values agreed at 90° and of course at 0. The results of a large series of such measurements and reductions are given below in Table I. It seems then as a reasonable result of these measurements and reductions, to assume that the vibrations of the torsion pendulum were angular harmonic. And this in turn gives us additional evidence of the validity here of Hooke's Law during the vibration.

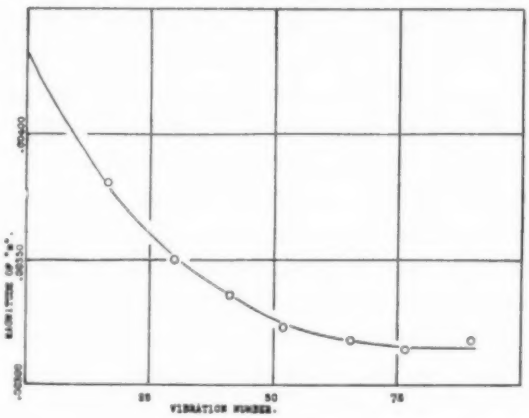


Fig. 4.

TABLE I.

θ	Const. sin θ.	Means of the Adjusted Ordinates.
0	0	0
15	3.32	3.29 ± .01
30	6.41	6.39 ± .02
45	9.06	9.03 ± .02
60	11.09	11.08 ± .02
75	12.37	12.35 ± .01
90	12.81	12.81 ± .01

It might be mentioned incidentally under this section that from the photographic records there was an opportunity of measuring the period, and amplitude of course, of the vibrating pendulum. These measurements give results identical with those obtained with the method of observation used in the preceding work, and so give one the assurance that the methods there used were sound.

4. *Effect of Long Continued Rest.*—The relation between amplitude and period in these pendulums is not by any means a constant one, as reference to former papers will make plain. Briefly, if the wire has been annealed at red heat, and then vibrated through not more than one or two degrees per cm. of length, its period is low and nearly constant over this range of vibration. However, if the same pendulum is vibrated or even twisted through ten or twelve degrees per unit length, and then vibrated through the same range as before, its period is found to be not only much larger but also to change much more rapidly with amplitude. These two points are shown in curves (*e*) and (*a*) respectively of Fig. 5.

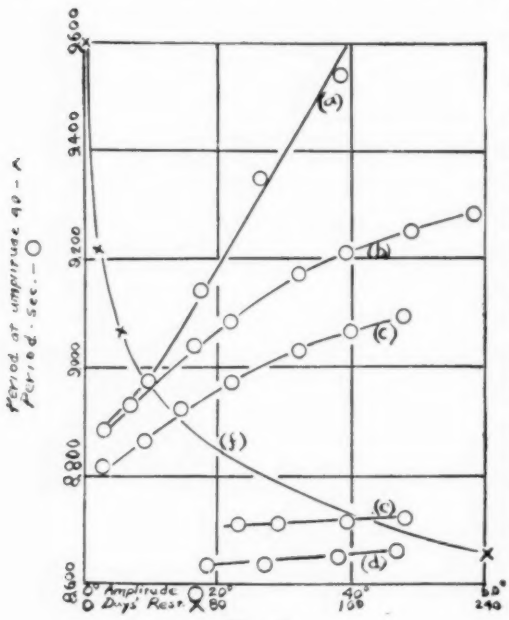


Fig. 5.

In all the experimental work the general method of wiping out the history of the wire was to anneal it under load at red heat. In every case this gave the wire the smallest period. By chance the wire had been left hanging for several months without having been annealed before this long period of rest. On vibrating the wire at the end of this period I was surprised to find from the relation between amplitude and period that the effect of the long rest had been not only similar to the effect of annealing, but that it had actually carried the wire beyond this point. Here was a case where the wire, as it were, automatically annealed itself. The results of this experiment are shown in curve (*d*), Fig. 5. To make certain of the matter, the wire was annealed and the old position of the curve for period and amplitude was obtained (curve (*e*)). Of course this suggested that there was a kind of recovery in the elastic condition

of the wire and to gain information on this point, observations were made after 22 hours' rest (curve (*b*)), and after 25 days' rest (curve (*c*)). The original observation had been made after 240 days' rest. In curve (*f*) of Fig. 5 is represented the relation between the period at a double amplitude of 40° and the number of days that the wire has rested. A general logarithmic recovery curve is clearly indicated.

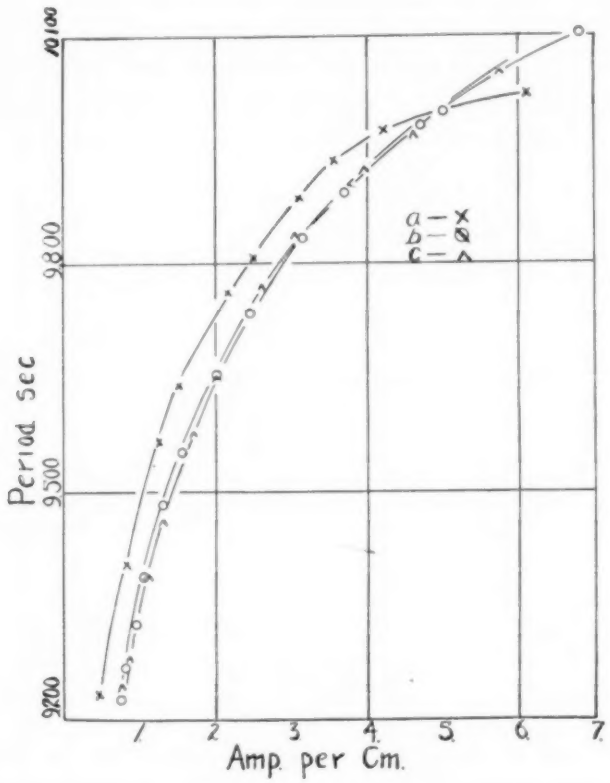


Fig. 6.

5. *Effect of Variation of Length of Wire, and Speed of Vibration.*—In a former paper[1] there were recorded results wherein it appeared to be indicated that even with a careful preliminary treatment of the wire there were differently shaped curves connecting period and amplitude for different periods of vibration. A valid objection to this former work would be that the air friction in the different cases would be so different with different velocities of vibration that the results for internal friction could not well be compared. In view of this a set of observations was made in which external friction was made practically constant. Whether

[1] PHYS. REV., XXXI., 1910, p. 449.

we assume the air friction to be dependent on the first, second, or other power of the velocity of vibration, the air resistance for varying lengths of the wire can be made the same by adjusting the periods so that they are proportional to the maximum amplitude of vibration. Since in the various cases the maximum amplitude of vibration is made proportional to the length of the wire, the period then, simply, is made proportional to the length. This was accomplished without changing the load on the wire, by sliding to or from the center two brass cylinders which fitted over a horizontal steel rod. The results are best explained from the three curves of Fig. 6. These curves are all reduced to the same scale

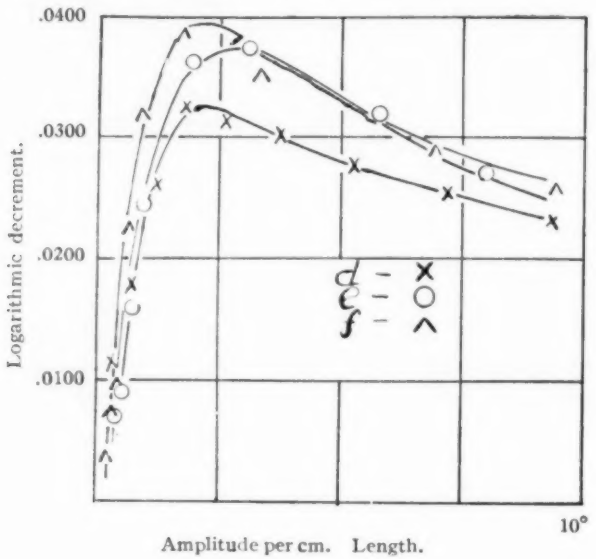


Fig. 7.

so that they can be compared. Curve (*a*) represents the longest wire, and the longest period of vibration; curve (*b*) represents the medium, and curve (*c*) the shortest wire and the shortest period of vibration. The effect noticed in the previous work is here verified. The faster the vibration the sooner the curve connecting period and amplitude turns down toward the *X*-axis. Of just what significance this is, is at present not clear.

In the above experiments with constant load, with constant initial twist per cm. of length, but with variable length of wire it is interesting to note the variation of the logarithmic decrement with the mean amplitude of vibration in the three cases considered above. These variations are shown in Fig. 7, where curves (*d*), (*e*), and (*f*) refer respectively to the conditions represented by curves (*a*), (*b*), and (*c*) of Fig. 6. Here

again is to be noted a progressive change wherein the shortest wire—likewise the one having the smallest period—has the largest decrement for a given amplitude. The peculiar shape of the logarithmic decrement amplitude curves has been previously noted.[1] It is to be observed that at a twist of from two to three degrees per unit length there is a sudden break, not only in the logarithmic decrement-amplitude curves, but also in the period-amplitude curves, as can be seen in Figs. 7 and 6 respectively.

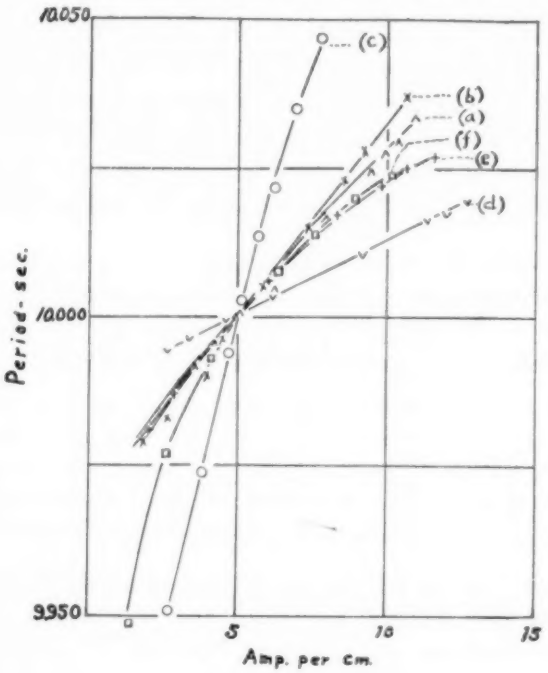


Fig. 8.

6. *Effect of Drawing.*—It was found practically impossible to draw the 40 per cent. wires with any plate we possessed, on account of the extreme brittleness of the wires. Even annealing at red heat had but small beneficial effect. Only with a very gradually graded draw plate could one have much hope of success in drawing down these wires. However, a wire of smaller percentage of iridium, probably 25 per cent., proved to be more easily drawn. The exact composition of this wire is not known. The following procedure was adopted. The wire was annealed and drawn down one size. A piece about 10 cm. long was cut from this, and the remaining part of the wire was again annealed and drawn through the next smaller hole. This was continued until three specimens, represent-

[1] Loc. cit.

ing three successive drawings were at hand. Each specimen was unannealed, but had been annealed just before its drawing. The only difference to be expected from these was that perhaps as the specimens grew smaller there would be a greater fraction of the wire affected by the drawing process. This is of significance in view of the following results. Two sets of experiments were performed. In the first one the three wires were used just as they came from the draw plate, and were vibrated under constant load, nearly constant length, constant initial twist per unit length, and with practically constant period. This latter was accomplished by varying the moment of inertia of the suspended system without changing its mass. In the second set of experiments the wires were first annealed at red heat and subsequently experimented on as in the first set. The results are most easily discussed from the curves of Fig. 8, and from the data in Table II. In Fig. 8 are platted the periods with amplitudes

TABLE II.

No. of Drawing.	Diameter of Wire (mm.).	No. of Vibrations from 12.5° to 4°.	State of Wire.
1	.181	170	unannealed
2	.163	158	unannealed
3	.151	66	unannealed
1	.181	280	annealed
2	.163	170	annealed
3	.151	104	annealed

for these wires. Curves (*a*), (*b*), and (*c*) represent respectively the conditions from the first, second, and third drawings of the wires in their freshly drawn condition, and curves (*d*), (*e*), and (*f*) represent the same wires after having been annealed. Two things will be observed. First the annealing acts to lower the period of a drawn wire just as it does to lower the period of a wire that has been vibrated for some time. Hence drawing and long-continued vibrations have similar effects on the wires. Secondly the effect of drawing becomes more and more pronounced the finer the wires become. This might be expected, for in the smaller wires the ratio of the surface to the volume becomes greater, in fact inversely as the radius, and the drawing apparently has most effect on the surface. In curve (*c*) we have a curve that is almost as pronounced as a similar curve for a 40 per cent. wire. It is evident then that to the quantities to which heretofore have been attributed the relation between period and amplitude, *i. e.*, to the per cent. of iridium, and the previous vibrational history of the wires, must be added the matter of the method used in the drawing of the wires. It will be noticed lastly that not even

an annealing at red heat is able to restore any of the drawn wires to the condition of the wire just larger than itself. Apparently the crystal structure has been so altered by the drawing that heating will not restore it. Probably long-continued rest under load, as described in section 4 of this paper, would restore all the wires to the same condition.

The effect of the drawing and the annealing is strikingly shown in another manner in Table II. In the third column is given the number of vibrations executed by the pendulum in dying down from an amplitude of 12°.5 per cm. to an amplitude of 4° per cm. The two effects mentioned in the above paragraph are here again clearly evident. In each case the annealed wire executes more vibrations over a given range of amplitude than the corresponding unannealed wire, and secondly the finer the wire in each set, the fewer vibrations there are in dying down over the amplitude range. It is certainly striking to have a wire whose cross-section is only two thirds of that of another wire of the same composition, die down in 66 vibrations, while the coarser wire continues to vibrate 170 times over the same range.

7. *Summary.*—Further study has been made of the elastic nature of platinum wires alloyed with iridium. The following points have been made:

(*a*) In spite of the peculiar variation of period with amplitude, and of the enormous change in the decrement of these wires as they die down in their vibrations, Hooke's Law has been found to hold, not only statically, but also kinetically.

(*b*) The torsional vibration of these wires has been proved to be practically angular harmonic.

(*c*) The elastic properties are profoundly modified by long-continued rest under load.

(*d*) With due allowance for the effects of ordinary external and internal friction, there is found to be a variation in the elastic properties of the wires with the speed of vibration, or at any rate with the period of vibration.

(*e*) The elastic properties are much modified by drawing the wires.

8. *Conclusion.*—It seems quite definite that all the observed phenomena connected with these alloys must be related to crystalline structure. Several attempts have been made to etch and examine cross-sections of these wires, but thus far no satisfactory specimens have been prepared. If we accept this hypothesis, then it is interesting to note how not only annealing and drawing can change the crystalline structure, but likewise strenuous vibration, and also long-continued rest. It is fortunate that common wires of pure metals and of alloys are not so sensitive to treat-

ment as are these. If they were, we should need in our laboratories the services of an expert historian, if we should ever expect to use the wires in exact measurements. That these effects are present in almost all wires, of course to a much smaller extent than in these platinum-iridium wires, is the belief of the writer, and further with these sensitive wires as exploring agents, we may hope to learn more concerning other elastic substances.

STATE UNIVERSITY OF IOWA,
July 22, 1912.

ANALYSIS OF COMPLEX SOUND WAVES.

By C. W. Hewlett.

THE object of this work was the analysis of the complex sound waves sent out by violins. The work is a continuation of that begun in this laboratory by Dr. P. H. Edwards (Phys. Rev., 32, Jan., 1911), who studied quantitatively the analysis of the sound waves sent out from several instruments including the violin, 'cello, flute, cornet and clarinet.

The same method was used by both Dr. Edwards and myself. A set of resonators each provided with a Rayleigh disc was used to analyze the waves. The resonators were cylindrical and were composed of two pieces of telescoping brass tubing, one piece being closed at one end with a solid disc of brass, and the other closed at one end with a disc of brass having a circular opening at its center. This opening was the mouth of the resonator. This arrangement enabled the resonators to be tuned over quite a wide range. A set of thirty-nine resonators was designed with frequencies ranging from 128 to 2,552 vibrations per second. They were constructed by Mr. Frank Smith, one of the mechanicians in this laboratory. A drawing showing the design of the resonators, and a table giving their dimensions is given farther on. The resonators were mounted side by side on the four shelves of a wooden case. This was a framework whose front sashes were covered with very thin celluloid, transparent to both light and sound; the other sashes being covered loosely with light tissue paper.

The room in which the experiments were carried out was approximately four meters each way. Reflections from the walls, floor and ceiling distort the sound waves to such an extent that absolute measurements of the intensity of a source would be almost impossible if some means were not devised to eliminate these disturbances. With this end in view the walls and ceiling were hung with a preparation of flax called Linofelt. This material is a fluffy, fibrous substance sewed between two strips of heavy paper. This was first suspended by wires so as to completely hide the ceiling and walls and then the strips were sewed together. The surface of the paper on the walls exposed to the room was then stripped off, leaving the soft hairy surface exposed. On account of the lack of mechanical strength of the material the paper was not stripped from the ceiling. The floor was also covered with Linofelt and then

with a layer of burlap. The reflections were greatly decreased, although not entirely destroyed.

The resonator system for measuring the intensity of sound was as follows: A thin mica disc whose diameter was about half that of the opening in the resonator was suspended by means of a fine quartz fiber close in the opening. A small glass rod attached to the lower side of the disc terminated in a small glass dumbbell which dipped into a cup of kerosene oil. The object of the dumbbell and oil was to damp the motions of the disc. In the center of the mica disc was fastened a small chip of platinized concave mirror. The disc was turned so that its plane made an angle of 45° approximately with the mouth of the resonator.

When the resonator responds to a tone of its frequency the disc experiences a couple whose magnitude depends upon the angle between the plane of the disc and that of the mouth. The disc will therefore turn till the couple due to the fiber is equal and opposite to that caused by the vibrating air. The formula given by Lord Rayleigh for this couple (Theory of Sound, Vol. II.) is

$$M = \tfrac{4}{3}\rho a^3 W^2 \sin 2\theta,$$

where a is the radius of the disc, W is the mean velocity of the vibrating particles of air, ρ is the density of the air, and θ is the inclination of the disc to the plane of the mouth. Now the couple may be calculated from a knowledge of the torsional moment of the fiber and the deflection, so that the mean kinetic energy per cubic centimeter of the air in the mouth of the resonator, $\frac{1}{2}\rho W^2$, may be calculated. Helmholtz has shown that the intensity of the waves which would exist at a given point were the resonator not there is to be obtained from that in the mouth of the resonator by multiplying by the factor $2R^3/\pi^2 S$, where R is the radius of the mouth and S is the volume of the resonator.

If δ is the deflection in degrees of the disc and if K is the torsional moment of its suspending fiber, then the moment acting on the disc due to the fiber is $2\pi\delta K/360$. When equilibrium has been established, the moment due to the vibrating air and that due to the fiber must be equal and opposite. Equating the two we have

$$\frac{2\pi\delta}{360} K = \tfrac{4}{3}\rho a^3 W^2 \sin 2\theta,$$

$$\frac{2\delta}{\sin 2\theta} = \frac{480}{\pi} \cdot \frac{a^3}{K} \cdot \rho W^2,$$

$$\text{Kinetic energy per cm}^3 = \tfrac{1}{2}\rho W^2 = \frac{\pi}{960} \cdot \frac{K}{a^3} \cdot \frac{2\delta}{\sin 2\theta}.$$

The kinetic energy per cubic centimeter in the air is the quantity we wish to determine when analyzing a complex wave. From the above formula it is seen that the kinetic energy per cubic centimeter in the air in the mouth of the resonator may be determined from a knowledge of δ, θ, and the ratio K/a^3. By using Helmholtz's formula for the multiplying power of a resonator the kinetic energy per cubic centimeter which would exist at that point if the resonator were not there may be calculated. It is thus seen that it is not necessary to know the torsional moment of the fiber and the radius of the disc separately. The method by which K/a^3 was determined will be discussed shortly.

A large translucent paper scale with vertical rulings 1 cm. apart was mounted in front of the case of resonators. The faces of the resonators were adjusted parallel to this screen. Four Nernst glowers, one for each shelf of the resonators, were provided with hoods each containing a small aperture. These were mounted at the sides of the case, the apertures facing small celluloid windows. The rays of light entering these windows were therefore perpendicular to the axis of the resonator.

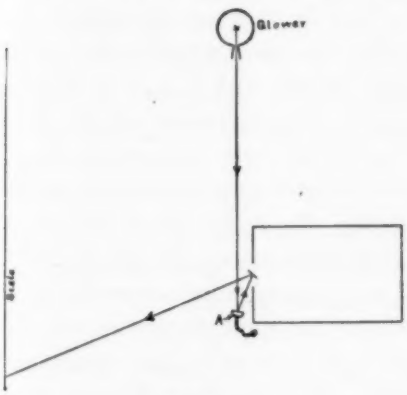


Fig. 1.

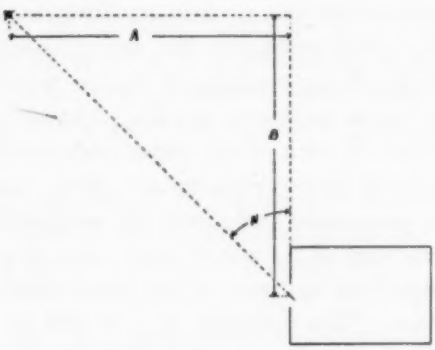


Fig. 2.

The disc was turned so that the chip of the mirror on its face was hidden from the glower and an auxiliary mirror A mounted on a lead wire served to illuminate its surface. By this means the image of the glower on the scale could be placed where desired without interfering with the disc or glower. The surface of the mica disc was blackened with soot to avoid reflections from its surface. The deflections on the scale were reduced to degrees by a graphical method. The angle between the disc and the face of the mouth of the resonator was found by placing the eye in the plane of the disc and then measuring the tangent of the angle. The zero of the image was noted at the same time.

$$\tan N = \frac{A}{B}.$$

This angle, of course, was the zero angle, but knowing the deflection, half its value could be subtracted from the zero angle thus giving the θ in Rayleigh's formula.

Edwards showed that, if the disc was very close in the opening of the resonator, the deflection produced by a sound of a given intensity was independent of the distance of the disc from the mouth. In the present work this experiment was repeated and found to agree with the work of Edwards when the size of the disc was small compared to that of the opening; but, if the disc was larger than half the opening, the deflection increased very rapidly with approach to the opening when this distance was small. It was found that with a disc whose diameter was half that of the opening the deflection was practically constant within a distance of about .1 of the diameter of the opening. All the suspensions hung within this distance, and those in front of the larger resonators were much closer.

The torsional moments K of three of the fibers were determined by measuring the periods of vibration in vacuum, first when loaded with the usual system of disc and glass damper, second with a small auxiliary load whose moment of inertia was known. The diameter of the disc was also measured and K/a^3 calculated for each of these three suspensions. K/a^3 for each of the suspensions used in the experiments was then determined by comparison with these standards. To make this comparison a suspension and one of the standard suspensions whose disc was nearest the size of the one which it was wished to compare were suspended successively in front of the same resonator at the same distance from its face. The resonator was excited by an organ pipe or another resonator blown by air kept at a constant pressure. We have from the equation previously given,

$$\frac{K}{a^3} = C\frac{\sin 2\theta}{2\delta}$$

where

$$C = \frac{480}{\pi}\rho W^2.$$

Using the standard suspension, C may be determined. The suspension for which K/a^3 was required was then substituted for the standard suspension and the deflection in degrees of the disc determined. θ the angle between the disc and the mouth of the resonator was also determined. Substituting these quantities in the previous equation K/a^3 was

calculated. K/a^3 was measured for all the suspensions at least three times, and the suspensions were compared among each other in order to get some idea as to the accuracy attainable. The results which are given further on are the averages of all the determinations and are probably correct to within 10 per cent. The comparison resonator was mounted at the center of curvature of a circular paper scale free to rotate about a perpendicular axis through its center of curvature. This scale was divided into degrees, so that the deflections were read directly in degrees. In this case the zero angles were determined by measuring the angle between the image when the disc lay flat against a piece of glass clapped over the opening of the resonator, and when hanging free.

A word should be said in regard to the way in which the resonators were tuned. A violin was first tuned by means of an "A" tuning fork, and then the resonators were tuned to the partials of the violin. The resonator was first tuned approximately by ear. It was then placed in its position back of its disc and its pitch found by playing the violin and sliding the finger along the string till a maximum deflection was obtained. The resonator was then sharpened or flattened as required by sliding the telescoping tubes, and the process repeated until the resonator was so exactly in tune that no difference could be observed between its pitch and the corresponding partial. The pitches of some of the partials of the different strings so nearly coincided that it was found possible in some cases to use the same resonator for a partial of two or three strings.

This work has been confined almost exclusively to the analysis of the quality of the tone from the open strings of violins, although when the apparatus was designed it was intended to include some other instruments. In making the tests the performer took his position in front of the case of resonators so as to hold the violin about the same distance from all the resonators. This distance was about 240 cm. The observer's position was in front of the scale but slightly to one side so as not to obstruct the waves on their way to the resonators. In taking a record, the performer drew the bow to and fro over the open string as evenly as possible several times in succession. On account of the varying intensity from one end of the stroke to the other, and the changes in quality as the position of the bow changed the positions of the spots of light on the scale were quite variable during this interval. However after some practice it was found possible to select a short interval during which the quality of the tone seemed the best and to locate the image with some accuracy. Thus during an interval of from five to ten drawings of the bow to and fro it was usually possible to form a pretty fair estimate of the

deflection for any one partial. This same process was repeated for each partial. The image giving the largest deflection was observed during the whole procedure, and it was ascertained that it kept on the average the same position throughout the test. Should its average position change owing to change of pitch or intensity the performer was immediately notified. It might be mentioned here, that invariably it was found comparatively easy to produce a tone of fairly constant intensity throughout the stroke on the best violins, while with violins of poor quality this was very difficult to do.

Constants for Fibers Used.

Numbers correspond to number of resonator with which the fibers were used.

No.	$Ka^3 \times 10^2$.	No.	$Ka^3 \times 10^2$.	No.	$Ka^3 \times 10^2$.	No.	$Ka^3 \times 10^2$.
1	3.4	11	21.1	21	1.93	31	4.34
2	12.3	12	19.7	22	135.0	32	8.0
3	2.0	13	69.0	23	2.23	33	3.88
4	24.8	14	18.9	24	62.5	34	21.30
5	6.9	15	36.5	25	80.4	35	2.97
6	6.5	16	3.91	26	4.59	36	4.52
7	4.8	17	125.0	27	7.61	37	1.08
8	15.0	18	21.4	28	61.30	38	8.74
9	6.4	19	46.3	29	1.61	39	3.00
10	274.0	20	36.4	30	.60		

K represents the torsional moment of the fiber and a the radius of the disc to which it is attached.

Number of Resonator System.	G-string.	Partials.		
		D-string.	A-string.	E-string.
5	1			
8		1		
11	2			
12			1	
15	3	2		
16				1
19	4			
21		3	2	
23	5			
26	6	4		
28			3	2
29	7			
30		5		
31	8			
33	9	6	4	
35	10			3
36		7		
37	11		5	
38	12	8		
39	13	9	6	4

In this investigation only certain of the above set of resonators and fibers were used. These are given on the following page, and it will be noted none of the suspensions for which K/a^3 is very large were used. The following are the partials of the open strings that were investigated. The number of the resonator system used with each partial is also given.

Results.

Below is a curve showing the necessity of keeping the size of the disc used well under the size of the opening in the resonator. In order to make the curves comparable, the deflections were expressed as percentages of the deflection which would exist if the suspension were placed in the mouth of the resonator, *i. e.*, at *o* distance from the mouth. This deflection was obtained by extrapolation.

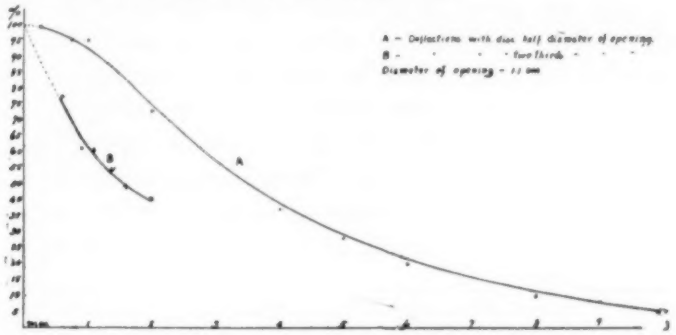
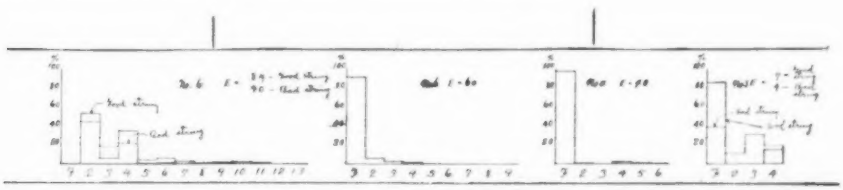


Fig. 3.

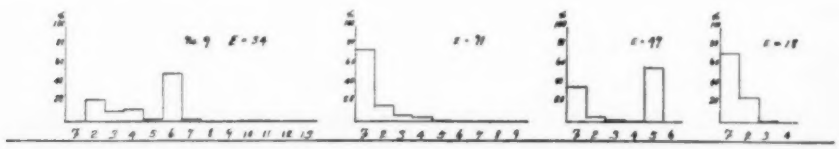
Records were made of the tone quality of twenty-nine violins and one viola. The records of a number of these instruments were made but once, while anywhere from two to six records of some of the others were made. A few of these records illustrating the points brought out in this work are reproduced at the end of this paper. It will be observed that each record is distinguished by a number. These numbers indicate approximately the order in which the records were made. The abscissæ represent the fundamental and successive partials of the string being played. The ordinate at any partial gives the energy in that partial expressed as a percentage of the total energy given out by the string. The energy per cubic centimeter, E, given out by each string is also given. To reduce to ergs per cubic centimeter multiply by 10^{-7}. The distance of the resonators from the position occupied by the violin when the record was being made was about 240 centimeters, so that the output of the violin may be calculated if one neglects the distortion of the waves due to reflections at the walls, and if it be assumed that the violin sends

out waves equally in all directions. The four curves in each set correspond to the open G, D, A, and E strings respectively, reading from left to right, unless otherwise specified.

There are differences in the quality of tone produced by different performers on the same instrument, sometimes even by the same performer at different times. However, fairly good agreement was usually obtained between the records made by the same performer on the same instrument under the same conditions. Some idea as to the degree in which the experiments could be repeated may be obtained by comparing the following two sets of records, (16, 18, 20), (24, 31, 37). The last group were all made by different performers playing with quite different degrees of loudness. The following groups of records are representative of some of the best instruments studied: (56, 57), 19, (16, 18, 20). Record 17 and the group (24, 31, 37) were made from two violins of exceedingly poor tone quality. The violins studied were roughly classified under three heads, the criterion being the general opinion of musical people in regard to the quality of the instrument. About one sixth of the instruments belonged to the class of the "Best Violins," about one sixth to the class of the "Poor Violins," and the remaining two thirds to the class of the "Ordinary Violins."



RECORDS 3 AND 6. These are the records of two violins bought in the white and finished and graduated by Mr. Della Torre. They have been treated with Mr. Della Torre's varnish and oil preparation. Both violins were made as much alike as possible. Record 3 is of the violin designated as "A," while record 6 is of the violin designated "W." Mr. Della Torre played for both records. It was found that both violins were beginning to "open up," *i. e.*, the glue holding the ribs, back and belly together had turned loose in one place. This may account for the fact that the tone was no better, as Dr. Edwards recorded the violins as having very good tone quality.

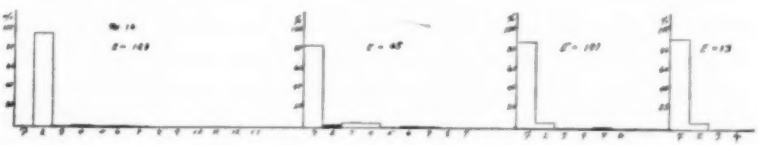


RECORD 9. This is a trade violin bought from Eisenbrandt, of Baltimore, by Mr. Della Torre for $5.00. It is designated by Mr. Della Torre as No. 2. This record, played by Mr. Della Torre, shows the violin as having a very poor weak tone. The sound post was directly under the bridge, and the base bar quite stiff.

Discussion of Records.

G-string.—The intensity of the fundamental of the G-string on all the violins is negligible in comparison to the second partial (first overtone). On all the best instruments the intensity of the second partial lies between 90 and 100 per cent. of the total intensity of the string. The third partial has an intensity of less than 10 per cent. of the total intensity of the string. After the third, the intensity of the partials drop off very rapidly, the fourth having less than 2 per cent. of the total intensity, there being no measurable energy beyond the sixth partial.

In the case of the poor violins, the second partial rarely has more than 60 per cent. of the total intensity and very often less than 20 to 30 per cent. The third partial is usually the strongest and attains at times more than 70 per cent. of the total intensity. In one case it was observed that the sixth partial contained 50 per cent. of the total intensity (see record 9). After the third partial the intensity is distributed among the partials as far out as the thirteenth, dying out very slowly in some cases. Nothing more general can be said in regard to the ordinary violins than that the second partial usually contains from 60 to 90 per cent. of the total intensity, the third and fourth partials being often quite prominent. Sometimes the third partial is the most prominent, but in this case it is probable that the merits of one of its other strings saves it.

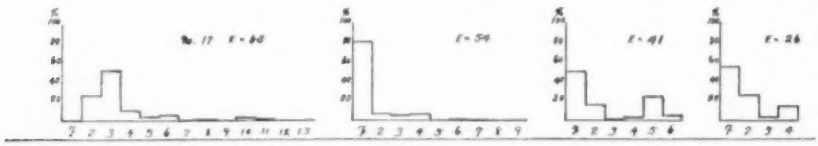


Record 16. This violin was made by Luther Heigis in 1911 and is numbered 106. The instrument has a fine tone quality, especially on the G string. Mr. Della Torre played for this record just before applying to it his oil preparation. The intensity of the playing was medium.

D-string.—On all the best violins the intensity of the fundamental on the D-string lies between 80 and 100 per cent. of the total intensity. The remaining 20 per cent. is distributed irregularly between the second third, and fourth partials, the fifth and sixth receiving some in some cases, but there is nothing beyond the sixth or seventh. On the poor violins the intensity of the fundamental may rise as high as 70 per cent. but usually is as low as 60 per cent. or lower. In one case it was found to be as low as 20 per cent., the second partial being 74 per cent. A peculiarity of these poor violins is the way in which the intensities of the successive partials fall off, "step" fashion (see records 24, 31, 37, 9). On the ordinary violins the fundamental of the D-string may have

intensities as low as 50 per cent. and as high as the best violins. Usually the intensity of the fundamental lies above 70 per cent. and very often the record appears very much the same as do those on the best violins.

A-string.—On the best instruments the intensity of the fundamental lies between 91 and 100 per cent. of total intensity. The intensity of the second partial is less than 8 per cent. while the third and fourth partials are absent. The fifth partial appears quite frequently in all classes of violins. In all the best violins it has an intensity of less than 6 per cent., and there is no energy in the sixth or higher partials. The intensity of the fundamental of the A-string on the poor violins may be anywhere from 30 per cent. to 90 per cent. or more of the total intensity.

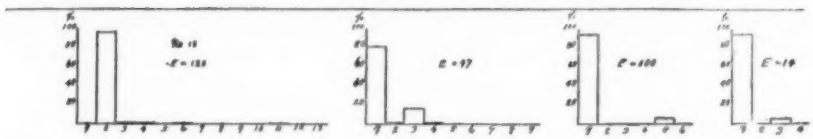


Record 17. This violin is owned by Mr. Grubmeyer, of Baltimore. It is a very poor "trade" violin, and has a tone which is very weak in intensity and poor in quality. Mr. Della Torre played for the record.

The intensity of the fundamental usually lies between 50 per cent. and 70 per cent. of the total intensity. The balance of the energy is irregularly distributed among the second, third, fourth, fifth and sixth overtones, the fifth overtone sometimes getting a large share (see record 9). The intensity of the fundamental on the A-string of the ordinary violins may lie between 70 per cent. and 95 per cent. of the total intensity, but most often lies between 80 per cent. and 95 per cent Some of them resemble the poor instruments in that the energy is scattered among the partials, while most of them approach the records given by the best instruments. .

E-string.—In the best violins the fundamental has an intensity of from 70 per cent. to 95 per cent. the total intensity. The balance of the energy appears quite irregularly distributed among the second, third, and fourth partials. It is hardly possible to make a distinction between the ordinary violins as a whole and the poor violins. In both classes the intensity of the fundamental is frequently between 70 per cent. and 95 per cent. Often however it falls below this, and occasionally the second, third, or fourth partial appears the most prominent.

All of the best violins have certain strings which are considered better than others. I have selected these best strings and plotted them on a single sheet which I have labelled "Ideal violin tone." The curves for all the best strings on the best violins fall within the shaded portions of these curves.

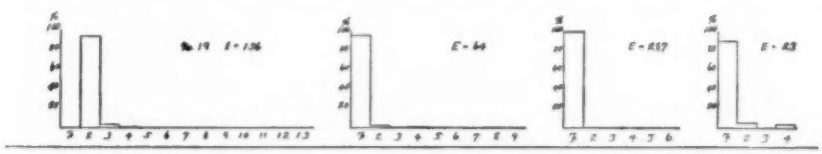


RECORD 18. Same violin as in Record 16. Mr. Della Torre played for this record two days later than for record 16, having applied the oil preparation in the meantime. The "A" string seemed to give a brighter tone than in the previous test. The intensity of the playing was moderate.

The effects of certain changes in the adjustment of the violin were also studied. It is seen that bad strings throw the energy out into the higher partials (see records 3 and 6).

It was thought that strings stopped by holding them down to the finger board with the fingers might give a tone in which the overtones were less prominent than with the open string. This was tried by playing the notes corresponding to the open D, A, and E strings on the G, D and A strings respectively. A comparison of records 20 and 57 will show, however, that while this may be true in some cases, it is not necessarily always true.

The effect of hard and soft bowing was tried at various times. Record 55 shows the results of forcing a very fine violin. Contrary to expectation the overtones are fewer and less intense than with the same instrument played lightly (see record 43). Record 20 shows the result of soft bowing on a good violin. Records 16 and 18 are for the same instrument when bowed with medium intensity. Again it does not appear that on the whole the number and relative intensities of the overtones are decreased. Record 31 represents a violin bowed with medium intensity, and 37 represents the same violin bowed softer.

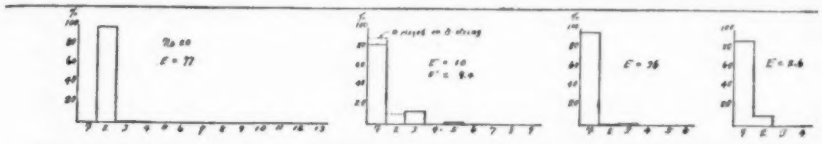


RECORD 19. This violin is owned by Professor Aperda, of Baltimore, the age and make of the instrument are unknown. The instrument has a very fine tone quality, and an exceptionally powerful "A" string. Mr. Della Torre played for the record.

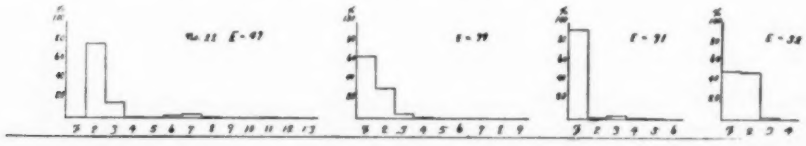
A violin was found in which the sound post was directly under the bridge. A record was made (9), and then the sound post was moved to its proper position back of the bridge. Another record (22) was then made. The total intensity of the sound was increased about 36 per cent. by this procedure, and a wonderful change produced in the relative intensities of the overtones, shifting the energy into the overtones of lower

frequency. The base bar of this same violin was found to be very thick. Two strips were accordingly removed, and a record made after each removal. Finally, the base bar was about half as thick as previously, the intensity about 50 per cent. greater than before the base bar was split and the overtones fewer and the energy more concentrated into the lower overtones (see record 54).

The reflections from the walls is one of the main difficulties in the work, and I would suggest that any one wishing to continue it devise some scheme to do away with walls or put them at a sufficiently great distance.



RECORD 20. Same violin as in records 16 and 18. Mr. Della Torre played for this record on the same date as for record 18. The playing was soft. The D played on the G string seems to be a purer tone than when played on the open strings.



RECORD 22. Same violin as in record 9. The sound post had just been moved to its proper position. It will be seen that the total intensity of the sound was 36 per cent. higher than the previous one. Mr. Della Torre played for the record.

It has been suggested to do the work in a very large tent. I think that the work should be carried on in some locailty where the evenings are calm. A collapsible covering should be built around the apparatus in a large field. When one wishes to work the covering could be removed.

SUMMARY.

1. Trustworthy records of the tone quality of several violins have been obtained.

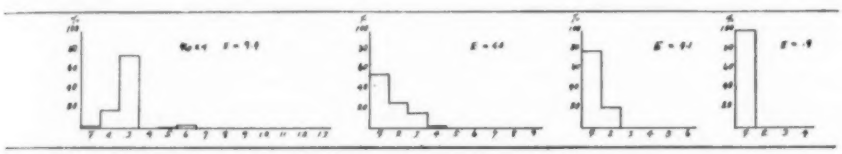
2. A set of curves has been drawn defining tentatively an ideal violin tone, the data being taken from the best violins obtainable.

3. Soft bowing does not necessarily produce a purer tone than medium bowing, and hard bowing does not necessarily produce a tone less pure than obtained with medium bowing.

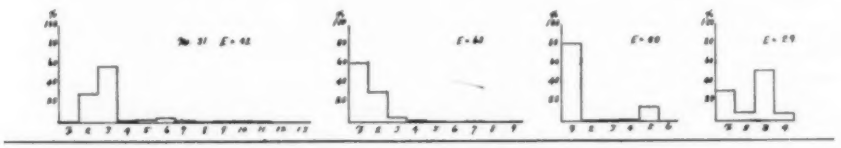
4. The method furnishes a powerful means of studying the effects produced by different kinds of strings and bridges, and by various changes produced in the adjustment of the sound post, base bar and bridge.

In conclusion I wish to thank Professor Ames, Dr. Anderson, Dr. Pfund

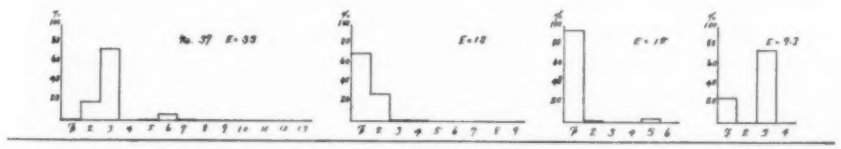
and others in the laboratory for their assistance and advice, and for the interest they have shown in my work. I wish also to thank numerous friends in the city and members of the Peabody Conservatory of Music for the loan of violins and for personal assistance in the work. In conducting this investigation I have had the great benefit of the advice and assistance of Mr. Frank Della Torre, of Baltimore. He placed at my disposal his entire collection of violins, which is a very fine one; he took apart and altered one of these violins for me, a kind of work in which he is exceptionally skillful; and he played various violins for me while I made the observations.



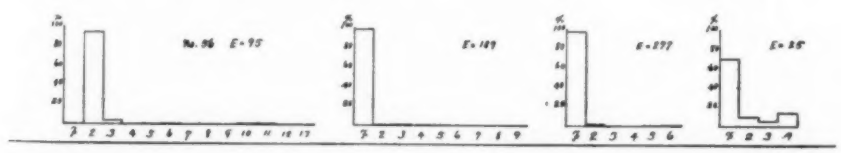
RECORD 24. This violin is owned by Mr. Wear, of Baltimore. It is a comparatively new and cheap instrument, with a weak, scratchy tone quality. The sound post was in front of the bridge. The writer played for this record, and having to make observations at the same time, he was located unsymmetrically with respect to the resonators.



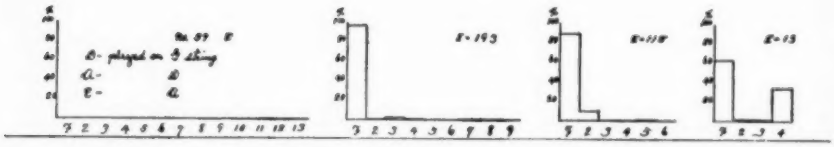
RECORD 31. Same violin as in record 24. Mr. Della Torre played for this record.



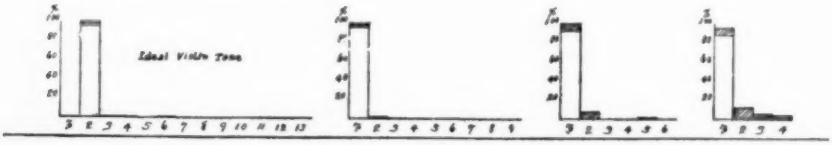
RECORD 37. Mr. Wear played for this record. He played more softly than did Mr. Della Torre in record as above.



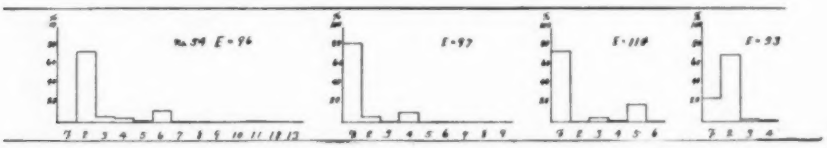
RECORD 56. Professor Van Hulsteyn's violin. This violin is a Regiera and has a very fine tone quality. The "E" string is the poorest string on the instrument. Professor Van Hulsteyn played for the record. The tone was pleasing, and the playing of medium intensity.



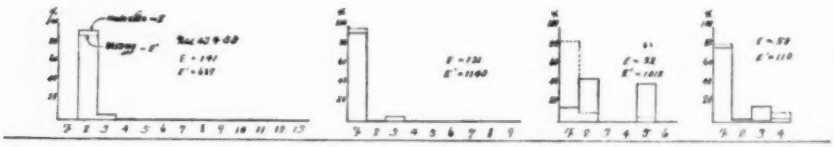
RECORD 57. Professor Van Hulsteyn's violin. The record consists of D played on the G string, A played on the D string and E played on the A string. Professor Van Hulsteyn played for the record, and the playing was of medium intensity.



Ideal violin tone. This set of curves represents tentatively the characteristics of the ideal violin tone. The characteristics of the best strings on the best violins tested fall within the shaded portions of these curves.



RECORD 54. Same violin as in record 9. Two strips had been removed from the base bar, so that the bar was about one half of its original width. The total intensity was about 100 per cent. greater than in record 9. Mr. Della Torre played for the record.



RECORDS 43 AND 55. Grancino violin (1727). This instrument has a powerful tone and a fine tone quality. Record 43 was made with Mr. Della Torre playing. The instrument was played lightly because louder playing sent the spots of light off the scale. Mr. Della Torre also played for record 55. The intensity of the sound was very great. An auxiliary scale was necessary to read the deflections. A bamboo was used. The tone quality of the instrument was very similar to that of Professor Van Hulsteyn's violin.

THE JOHNS HOPKINS UNIVERSITY,
June 4, 1912.

A NEW METHOD OF PHOTOGRAPHING SOUND WAVES.

By Arthur L. Foley and Wilmer H. Souder.

AT the Chicago meeting of the American Physical Society in 1905, the senior author of this paper exhibited photographs of interference and diffraction fringes about electric discharges and fluid streams, taken by what might be called the point source shadow method.[1] The light from a point source is allowed to fall directly upon a photographic dry plate several meters distant from the source. About half way between the source and the plate is placed the fluid stream or whatever is to produce a shadow on the plate. Say the object is a stream of warm air issuing from a glass tube. The air stream maintains for a time a more or less definite lateral surface and produces diffraction fringes on the plate. The light is refracted on passing through the stream of air of density differing from the air about it, and so the stream casts a sort of shadow on the plate. The method is so sensitive that it gives a shadow of a stream of water in water. Inasmuch as a sound wave in air consists of a compression and rarefaction, the method should enable one to photograph the shadow of a wave, provided a sufficiently strong instantaneous point source of light is obtainable. Mr. Wilmer H. Souder, while teaching fellow at Indiana University, undertook the problem and succeeded in obtaining sound wave photographs, but discontinued the work to accept a position elsewhere. The writer continued and extended the work, and succeeded in obtaining a light source many times as intense as the source previously used—so intense that, in photographing sound waves, no further increase is desirable.

The general arrangement of the apparatus in this experiment is shown in Fig. 1.

The sound wave is produced by an electric spark at the spark gap S, which will be called the sound gap. The light is produced by a second spark at the illuminator gap I, which will be called the light gap. If the sparks at I and S are simultaneous the light from I passes S before the sound wave emerges from behind the spark terminals. If the time interval between the sparks is any considerable fraction of a second the

[1] "Diffraction Fringes from Electric Discharges and from Fluid Streams," A. L. Foley and J. H. Haseman, Physical Review, Vol. 20, 1905, page 399; Proceedings Indiana Academy of Science, 1904, p. 206.

sound wave at S passes out of the field before the light from I reaches S. But when the interval between the two sparks is properly timed the sound wave at S casts its shadow on the photographic dry plate P.

The spark gaps S and I are connected in series to the spark knobs K, K_0 which receive sparks from T, T_0, the terminals of a large electric induction machine having four rotating mica plates thirty inches in diameter, driven by a variable speed electric motor. The length of the spark gaps T–K and T_0–K_0 is adjusted by sliding T and T_0 horizontally, or by moving K and K_0 vertically. Glass plates G and G_0 about twenty centimeters square are fastened to a wooden bar or rod R,

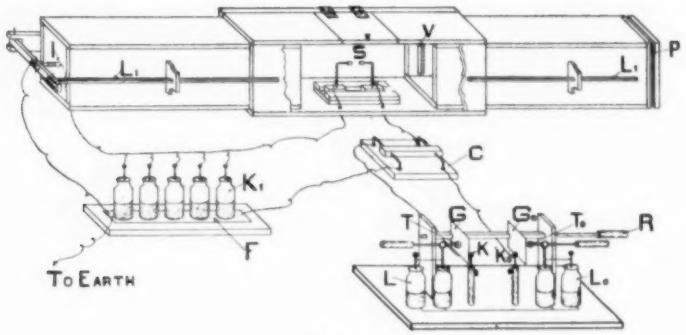


Fig. 1.

arranged so that it can be rotated on a horizontal axis. In the position shown in the figure the plates are directly between the spark knobs T and K, and T_0 and K_0, thus preventing a spark. A quarter turn of the handle of the rod R removes the plates and allows the spark to pass. In practice, however, it was found best to make the spark gaps T–K and T_0–K_0 just long enough to prevent sparking when the glass plates are out of the field. Rotating the rod then causes a spark just as the edges of the plates pass through the gaps.

To get a strong sound wave at S and an intense light at I, the sparks to the knobs K, K_0 should be heavy, consequently from one to three Leyden jars L, L_0 are put in multiple with each of the jars on the machine itself. Most of the work was done with one additional jar connected to each of the machine jars.

The knobs K, K_0 are connected to the gaps S and I through a large commutator C. Thus the direction of the spark at the gaps is readily changed. It was found that the apparatus worked about equally well with the spark in either direction. The chief effect of reversing the spark direction appeared to be a slight change in the time intervals of the sound and light sparks.

The sound gap S is in series with the light gap I, nevertheless the spark at S occurs before the one at I, because of the capacity K_1 which is in multiple with the gap I, as shown in the figure. The capacity K_1 consists of from two to eight Leyden jars of the usual type, standing on a sheet of tinfoil F, with one coat connected to earth. The time interval between the sound and light sparks depends on the capacity K_1, the greater the capacity the greater the interval. However it is not at all necessary to have here a variable condenser or one made up of small units. One can vary the capacity K_1 between rather large limits and still keep the proper time interval by varying the circuit in other ways. The time interval is increased by decreasing the capacity L, L_0, by decreasing the length of the spark gaps T–K and T_0–K_0, by decreasing the length of the sound gap S, and by increasing the length of the light gap I, the last having the greatest effect. One can vary the capacity K_1 by a hundred per cent. and readily maintain an approximately constant time interval between the sound and light sparks by merely changing the length of the light gap. The length of this gap is adjusted by means of the lever arrangement L_1, L_1, as will be understood by reference to both Figs. 1 and 2.

Fig. 2 is a cross section of the light gap, the spark taking place between

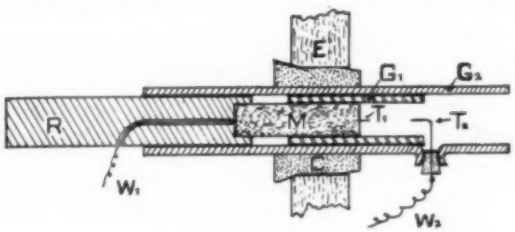


Fig. 2.

the terminals T_1 and T_2. T_1 is a short piece of No. 24 magnesium wire in the end of a metal cylinder M which is fastened in the end of a hard rubber rod R about 1.4 cm. in diameter and 10 cm. long. A wire W passing through a hole drilled in the rubber rod R connects the metal cylinder M, and therefore T_1, with one terminal of the electric machine. G_1 is a glass tube .7 cm. in diameter and 5 cm. long, fitting tight in a glass tube G_2, which is 1.4 cm. in diameter and 18 cm. long. G_2 passes through a cork C in the end E of a wooden box made of inch lumber. The rubber rod R slides back and forth (like a piston) in the tube G_2, and thus moves M back and forth in the tube G_1, and so changes the length of the spark gap T_1, T_2. Fig. 1 shows how R is connected to the lever arrangement L_1, L_1, which passes to the other end of the box and enables

the observer there to change the light gap at will while the sparks are passing, and thus regulate the time interval, and consequently the size (diameter) of the sound wave.

T_2 is a piece of No. 24 magnesium wire passing through a cork to the wire W_2 connecting with the terminal of the sound gap. The other end of T_2 is bent at right angles as shown in the figure and adjusted so that the spark takes place along the axis of the tube G_1. The wire T_2 is so small that its shadow is practically negligible. The source is thus an end on spark—itself practically a point source. Considerable light must be reflected from the end of the cylinder M and the walls of the glass tube G_1, the tube acting as a sort of gun to direct the light toward the photographic plate. But inasmuch as the tube is only seven millimeters in diameter and the plate is several meters distant, the entire source is relatively a point source.

The light gap is at one end, the photographic plate at the other end, and the sound gap near the center, of a long light-tight wooden box or tube consisting of three sections, the two end sections telescoping into the central section, all painted black inside. This combination permits of a quick and independent variation of the distance between the light and sound gaps, and between the sound gap and the dry plate.

The central section of the tube is four feet long and fourteen inches square inside. The end sections three feet long and twelve inches square inside, all made from planks one inch thick. Two additional sections, not shown in the figure, were sometimes used to get still greater distances between the gaps. Most of the pictures shown in this paper were obtained with the sound gap about one hundred and thirty centimeters from the light gap, and about a meter from the dry plate.

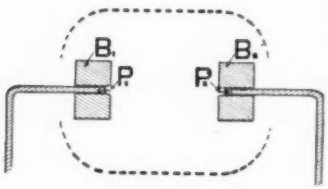


Fig. 3.

The front side of the central section of the box is cut away in Fig. 1, to show the general arrangement of the sound gap.

Fig. 3 shows the details of the gap itself. P_1 and P_2 are the platinum terminals between which the sound spark occurs. These consist of short pieces (.5 cm. long) of No. 20 platinum wire soldered in the ends of brass rods bent as shown. The brass rods are held by wooden blocks arranged to slide snugly between two cleats or guides fastened on a wooden base, permitting an easy adjustment of the length of the sound gap. The two halves of the sound gap are adjusted so as to be in the same plane with the light gap so as to give but one shadow of the terminals on the photographic plate, and also, as will be explained later, to give the best shadow of the sound wave.

The sound gap must be made long enough and the intensity of the spark great enough to produce a strong sound wave, if a distinct wave shadow is to be obtained. Consequently more or less light is produced at the sound gap, where it is not wanted. Moreover the sound gap is much nearer the dry plate than is the light gap. Fogging of the dry plate by light from the sound gap is prevented by three things:

First. The intensity of the light produced between the platinum terminals of the sound gap is far less than between the magnesium terminals of the light gap in series with it. Interchange the platinum and magnesium terminals and the plate is fogged by the light from the sound gap and the light gap fails to give enough light to produce clear shadows on the photographic plate.

Second. When the sound gap is in its usual position, axial with wooden box and light gap—its light is intercepted by one of the two hard rubber cylinders or buttons, B_1, B_2, shown in section in Fig. 3. In the axial position the buttons and their supports cast but one shadow on the plate, as seen in all the accompanying sound wave pictures except the first two.

Third. The walls of both the end sections of the box are provided with numerous tin vanes, only one, V, being shown in Fig. 1. These vanes are made of tin strips about an inch wide and twelve inches long, painted black, with one edge tacked to the inside of the box, the other edge being bent inward from the walls of the box so as to point toward the light gap. These vanes intercept almost all the light that otherwise might be reflected by the walls of the box and produce fogging of the plate.

The photographic plate P is carried in an ordinary 8 inch by 10 inch plate holder placed in the reversible back taken from an 8×10 camera. The end of the box was arranged to fit the camera back, light tight, in either position, of the plate. When the plate holder is removed the sound wave shadow falls directly on the ground glass of the camera back, and is distinctly seen by an observer looking through the glass along the axis of the tube; that is, with the eyes in line with the light and sound gaps and the center of the ground glass. If the experiment is carried on in a darkened room the wave shadow on the ground glass can be seen at a distance of several meters even when the glass is viewed obliquely, therefore the waves can be seen by several observers at the same time. Indeed the camera end of the box may be removed entirely and the shadow be allowed to fall on a white screen, or better, on a large sheet of white paper, and the waves be seen by reflection. The author has used this method in exhibiting the waves simultaneously to a number of observers. The screen is placed so the light strikes it obliquely. This

gives a distorted image of the waves, but it enables one to seat all the observers in a single group in front of the apparatus. But little time has been given to the problem of exhibiting sound waves on a large scale to large classes. The partial success attained leads the writer to believe that it can be done. Further details may be expected later.

In Fig. 1 the connecting wires are shown looped in the conventional way in order that the connections may be easily traced. In the experiment the wires were run through glass insulating tubes and as nearly straight as possible. Most of the connections were soldered. In fact many precautions must be taken if one is to obtain even an approach to regularity in the time interval between the sound and light sparks. One must be able to regulate the time interval and maintain it approximately constant, or he may expose photographic plates by the dozen and not once catch the sound wave in the position desired. By experience the writer finds that the following conditions give the best results:

The connecting wires should be of ample size. Small wires (No. 30) appear to slow down the spark and so decrease the intensity of the sound wave and the brightness of the light spark. And the tendency of the discharge to jump from the wires is much greater than when larger (No. 14) wires are used.

The Leyden jars, particularly those on the electric machine and in multiple with it, should not have the usual dangling chain for connection with the inner surface. The connection between the links of the chain and between the chain and the metal lining of the jar is entirely too haphazard to produce the regularity of charge and discharge required in this experiment. The dangling chain is a makeshift in any case.

In this experiment the jars were of the type frequently furnished with large oscillator sets. The short metal rod and dangling chain were replaced by a long rod—reaching almost to the bottom of the jar. On the end of the rod there was soldered a star-shaped disk of thin spring copper with the several radial arms bent so as to make spring contact with the inner tin foil coat of the jar. The results obtained with such jars are far more regular than those which are obtained when using chain connection jars.

From Fig. 2 it will be noted that the outer glass tube G_2 extends some distance beyond the limits of the gap and inner tube. The extension is not primarily for the purpose of reflecting the light toward the sound gap—the gun effect previously mentioned. It is to prevent rapid changes in the gas about the spark gap. Consider what happens when a spark occurs—at the sound gap for instance. The heavy discharge heats the air to a high temperature and convection currents are set up. Besides,

the spark itself violently disturbs the air because of its explosive character. If the spark is in the open the heated and ionized air mixes readily with the air about it so that a second spark takes place in air of varying character. The degree of ionization of the air about the gap depends then upon the time between successive sparks. If the spark takes place in a tube, as shown in Fig. 2, the air about the gap is prevented from mixing rapidly with the air that has not been ionized. Rapid changes in the resistance of the light spark gap are thus prevented and a more nearly constant time interval between the sound and light sparks made possible. At best this interval cannot be made exactly constant. Our knowledge of sparks and spark gaps is too limited. Some of their actions appear to be quite erratic.

There is little need of giving dimensions of capacities, spark gaps, etc., as these may vary greatly among themselves and still give results. Moreover the arrangement that appears to give the best results one day does not necessarily give the best results another day, when the atmospheric and other conditions are entirely different.

Let us suppose the capacities L, L_0, of Fig. 1 consist respectively of three Leyden jars, including the one on either terminal of the machine. Besides the Leyden jar capacity there is the added capacity of the machine itself, which is considerable in the case of a machine of the size and construction used in this experiment. Suppose further that six Leyden jars are used as the capacity K_1 and that the sound gap S is made about 3.5 cm. long. The speed of the electric machine is then adjusted so that sparks will almost, but not quite, pass when the gaps TK and T_0K_0 are made, say, six and seven cm. long respectively. As explained elsewhere a spark will then occur when the rod R is rotated so as to bring the edge of the glass plates, G, G_0, between the spark knobs. Sparks continue to pass if the glass plates are not immediately rotated out of the field. By a rapid to and fro rotation of the plates single sparks can be produced at will. This may be done by the observer himself, but preferably by an assistant. The observer stations himself so as to view the ground glass normally and by pulling the lever L_1 makes the light gap very short, say 1 cm. long. The assistant then produces sparks at regular intervals, say 1.5 seconds. If these intervals are not approximately constant the time intervals between the sound and light sparks will vary greatly due to variation in the ionization of the air about the spark gaps, the potential of the Leyden jars, etc. At every spark the observer sees the shadow of the sound gap terminals and, if the interval between the sound and light sparks is within the proper limits, he sees also the shadow of the sound wave produced at the sound gap. If he sees no

sound wave at all, but sees about the shadow of the terminals a cloud resembling a puff of smoke, it indicates that the time interval between the sound and light gaps is too long, that the sound wave has passed beyond the limits of the field and that the hot air from the spark has had time to pass out from behind the sound gap terminals, as shown in Photographs 9 and 10. The time interval must be made less. Since the length of the light gap is already a minimum the interval should be decreased by decreasing the capacity K_1 by removing one or more jars.

If the observer sees neither sound wave nor cloud about the sound gap terminals it indicates that the interval between the sound and light sparks is so short that the sound wave has not had time to emerge from behind the terminals—rather from behind the cylindrical buttons shown in Fig. 3. The observer readily increases the interval by pushing the lever L_1 and thus lengthening the light gap. If the latter is made much longer than the sound gap, sparks will not pass at the light gap. The best illumination is obtained when the light gap is about two thirds as long as the sound gap, say about 2.5 cm. long. If at this length the interval between the two sparks is still too short to show the sound wave, the interval is increased by increasing the capacity K_1. To get the best results it may be necessary to vary the lengths of the machine spark gaps and possibly the length of the sound gap. The latter is reached through a door or lid in the central section of the box. The effect of changing the length of these gaps is discussed earlier in this paper. Several adjustments and trials may be necessary before the sound wave appears. When it does appear it repays all the time spent in trying to get it, for—if the conditions under which the wave is formed are at all favorable—the wave shadow will stand out with surprising definition and brilliancy whether reflected, refracted, or diffracted.

At first thought it might appear that the sound waves are spherical and that their shadows should be disks, not circles, as shown in the accompanying photographs. In the case of a linear spark the waves are not spherical, but cylindrical—with curved ends. In Fig. 3 the dotted lines represent a longitudinal section of the cylindrical wave that one would expect from a spark between the points P_1, P_2. The cylindrical buttons B_1, B_2 keep the wave cylindrical until it passes beyond them. The wave then takes on curved ends due to diffraction, but the intensity of the wave at the ends is far less than on the sides. In Fig. 3 the intensity of different parts of the wave is indicated by the breadth of the dotted lines. That this representation is valid is shown by photographs 1 and 2. To obtain these pictures the sound gap was turned at right angles to the position shown in Fig. 1; that is, the sound spark was at right

angles to the axis of the tube and therefore perpendicular to the path of the light from the light gap.

A moment's consideration will show why the wave shadows are always cross sections of the wave—why, in all the pictures except the first two, we do not see any shadow of the ends of the cylindrical wave. In the first place, the energy of the wave is relatively much smaller at the ends than at the sides. This means that the change in the density of the air is less at the ends than at the sides, and that light waves in passing through the ends of the sound wave suffer less change in their velocity than when passing through the sides of the wave.

In the second place, whatever deviation is produced in the light ray in passing through one end of the cylinder is largely counter-acted by the opposite deviation produced in passing through the other end.

The only rays of light that undergo uncompensated prismatic deviation are those that lie just inside the surface produced by drawing a system of tangents from the point light source to the sound wave. These light rays enter the sound wave with a large incident angle, pass along approximately parallel to the sound wave front without passing through the inner surface of the wave at all, and pass out near the other end of the lateral surface at a large angle of emergence. Such rays are deviated more or less and so change the otherwise uniform distribution of light on the plate, giving a shadow of that portion of the sound wave. In any case the only parts of a sound wave that give strong shadows are those to which tangents can be drawn that are parallel (approximately) to the light rays from the light gap. Thus the shadow closely represents a meridian section of the sound wave at right angles to the path of the light from the light gap.

In the early part of this investigation and before the light gap described in this paper was devised, single sparks at the light gap failed to give sufficient light to produce strong negatives. The most sensitive plates of four different manufacturers were tried—with little difference in the results. Indeed the differences between rapid and slow plates exposed to the light of a spark between magnesium terminals is far less than it is when they are exposed in the usual way, to a light much less intense but which lasts hundreds, perhaps thousands, of times as long—even when the exposure is made with a so-called instantaneous camera shutter. Most of the work of this experiment was done with Cramer's Crown plates and a strong hydrochinon (contrast) developer. To save time the plates were developed and fixed in an Eastman tank, a dozen plates at a time. The time of development varied from ten to twenty minutes.

So far as the writer knows all previous work on the visualization or

photography of sound waves has been by the so-called "Schlieren Methode" devised by A. Toepler,[1] and used by Mach,[2] M. Toepler[3] and Wood.[4] The Toepler Schlieren method is exceedingly ingenious and has very wide application. However, compared with it, the method described in this paper has some obvious advantages.

In the first place no high grade lenses or concave mirrors are required. All optical part are dispensed with.

In the second place the size of the sound wave is not limited by the diameter of a lens or concave mirror, but only by the size of the photographic plate or screen on which the wave shadow is to fall. Since the sound wave can be large, so can the sound lens, the sound gratings, etc.

In the third place, the wave shadow itself may be seen and photographed full size. By the Schlieren method the wave images are small, usually but a few millimeters in diameter. This makes it difficult to study the waves visually and impossible to exhibit them to a class. This defect cannot be overcome by changing the lens system, for the size of the images is limited by the lack of light, most of the light being cut off by the diaphragms which the Schlieren method requires.

In the fourth place the method in this investigation gives a field of uniform illumination and distinct sound wave shadows in all points of the field. The Schlieren method gives a field of varying and uncertain illumination and wave images much more definite at some than at other points of the field.

Details of Sound Wave Photographs.

Photograph 1. A longitudinal section of a sound wave from a linear spark at right angles to the axis of the tube, showing that the wave is cylindrical with approximately hemispherical ends. (Compare with Fig. 3.) In this position the light from the sound spark falls directly on the photographic plate and fogs it, and on this plate the light from the light gap superposes the shadow of the sound gap and the sound wave. Distinct sound wave shadows cannot be expected under such conditions. However the photograph shows that the wave form corresponds with the theoretical form shown in Fig. 3.

Photograph 1 shows also that *the luminous discharge in air at normal pressure is striated.* On the original negative the striations are quite distinct. Moreover, besides the principal sound wave the negative shows other systems of sound waves. This method of study promises to

[1] A. Toepler, Pogg. Am., 131, p. 33, N. 180, 1867.

[2] E. Mach, Sitzungsber. d. k. Akad. d. Wissensch. zu Wien, 98, p. 1333, 1889.

[3] M. Toepler, Ann. d. Phys., 14, p. 838, 1904. Also Ann. d. Phys., 27, p. 1043, 1908.

[4] R. W. Wood, Phil. Mag., 48, p. 218, 1899. Also Phil. Mag., 50, p. 148, 1900.

enlarge our knowledge of the conditions attendant upon the spark discharge in air. The writer will soon publish the result of his investigation of the subject.

Photograph 2. This photograph is the same as photograph 1, except that the direct light from the sound spark gap is prevented from falling on the photographic plate by placing between the gap and plate a small rectangular block of wood supported on a metal rod.

Photograph 3. A sound wave just emerging from behind the spark terminal. For this photograph and all the others except Nos. 1 and 2, the spark was axial with the tube, in the position shown in Fig. 1.

Photographs 4, 5, 6, 7, and 8 show the wave as it gradually travels outward from the source until it finally passes beyond the limits of the plate.

Photograph 9. Here the sound wave has passed beyond the limits of the plate and the hot air produced by the sound gap has had time to puff outward from behind the spark buttons. It will be noticed that in photograph 8 the puff has just begun to emerge from behind the buttons.

Photograph 10. The puff at a still later time than shown in Photograph No. 9. The photograph shows how clearly changes of temperature and pressure are recorded by this method.

Photographs 11 and 12 show a wave reflected at the plane surface of a piece of glass plate about 10 cm. wide and 20 cm. long, held vertically a short distance from the spark gap, with the surface of the plate parallel with the gap.

Photograph 13. This shows a wave (cylindrical) reflected from a concave cylindrical reflector. The reflector was made from a piece of lead about 6 cm. square bent around a gas pipe and held at the end of a vertical strip of sheet brass to which the reflector was soldered. Note the reflected wave front, and the reflected and diffracted waves about the edges of the reflector which are parallel to the spark gap.

Photograph 14. Wave reflected from a convex surface, here the surface of a cylindrical convex lens as described in the next paragraph.

Photograph 15. A plane wave produced by placing the spark gap at the principal focus of a convex lens of sulphur dioxide gas. The lens was constructed as follows:

A block of wood, *W*, Fig. 4, was shaped like a cylindrical lens about 10 cm. long, 4 cm. wide, and of the thickness desired,—almost 2 cm. in the case of the lens used in photograph 15, more than 3 cm. in photographs 16, 17 and 18. To form the lens space *L* a section 5 cm. long was cut from the center of the block, except for a narrow strip *S* at the bottom, to hold the end sections in place. A rubber band *B* was stretched between

the two extreme ends at the upper edge of the block and a portion of the thin edge of the block cut away just under the band so the band might be as free to move as possible. The sides of the block near the ends and the lower cross strip (the surface shaded in the figure) were coated with a light coat of thin shellac varnish. Before the shellac had time to dry the block was covered with a single collodion film with the lap on the wood strip S, and everywhere made gas tight by the shellac; thus forming between the collodion surfaces a cylindrical gas lens, L. The rubber band B was to keep the surfaces in position and still permit of considerable distortion of the walls of the lens without tearing the film. This was not possible when the films were pasted on lens forms having both an upper and lower rigid strip (S) and when the films were pasted to the form up to or close to the lens space L. A very few sound sparks invariably sufficed to rupture the films on such lenses, the rupture always being on the side away from the sound spark. There was no rupture when using a lens of the construction shown in Fig. 4. The points of attachment of the edges of the film are so far apart that the film has considerable freedom of motion, and is therefore not so easily ruptured. Obviously the freedom of motion is still further increased by the use of the rubber band B.

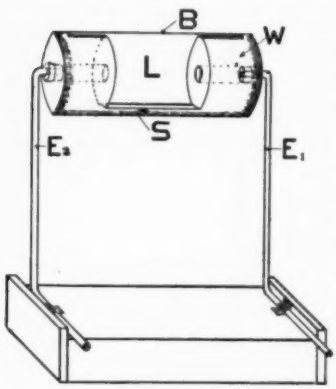


Fig. 4.

Collodion films are exceedingly strong considering their thickness, but they are rather stiff and they will not stretch without tearing. The writer found that a film made of so-called "liquid skin" is more flexible and extensible. The formula for the liquid skin is: 92 gm. collodion, 5 gm. Canada balsam, 3 gm. castor oil. When thoroughly mixed and free from air bubbles a small quantity of the fluid is mixed with three or four times its volume of ether. This is then poured into a glass dish with a flat bottom, or on a piece of glass plate, and the dish or plate drained at once by standing on edge. When the film is thoroughly dry it is floated off in the usual way—by allowing water to creep in between the film and the glass. The film should dry thoroughly before one attempts to mount it.

The gas is introduced into the lens L through a small glass tube E_1 connected with the gas generator. The gas escapes from the lens by means of the glass tube E_2, to which a long rubber tube is attached so that the gas can be passed into a hood or out at a window. The tube E_2 is

larger than E_1, so that there may be no danger of the gas pressure increasing in L, and rupturing the film. A continuous flow of gas through the lens was maintained whenever the lens was in use. The sulphur dioxide gas was generated by the action of hot concentrated sulphuric acid on copper and the flow of gas controlled by regulating the heat. The pressure of the gas in the generator was maintained at about 5 cm. of water, as indicated by a manometer attached to the generator.

All of the lens photographs show the original wave, the wave reflected from the convex surface of the lens, the refracted wave, and the wave diffracted about the upper and lower edges of the lens. The film of the lens in photograph 15 has a minute perforation in it through which the SO_2 gas escapes. The path of the escaping gas is clearly indicated.

Photograph 16. A sulphur dioxide lens—thicker than the lens of photograph 15. Here the divergent sound wave has been rendered convergent.

Photograph 17. A carbon dioxide lens. Here the refracted wave is still divergent; that is, the spark gap is nearer the lens than the principal focus.

Photograph 18. A hydrogen lens. Here, contrary to what one should expect from the velocity equation, the refracted wave has suffered practically no change in curvature. In fact the several pictures appear to indicate that the velocity of the sound wave of an explosive character is not given by the Newton equation. This fact has been observed by others.[1] The author will discuss the subject more fully in a later paper.

Photographs 19 and 20. Sound waves reflected from a parabolic reflector made from a sheet of lead 6 cm. wide and 20 cm. long and supported by an upright strip of brass as shown in the photographs. The spark gap was placed at the focus of the parabola. The reflected wave is plane except (photograph 20) for the disturbance produced by the hot air through which the central part of the wave must pass.

Photographs 21, 22, 23 and 24 show four different positions of the sound wave reflected by an elliptical reflector. The reflector was made from a strip of sheet lead about 5 cm. wide and 25 cm. long bent into the form of an ellipse and the two ends of the lead sheet soldered together. It was supported on a block of wood cupped to fit it. The brass rods that support the spark terminals are so far apart (see Fig. 3) that the lead reflector is readily placed in position between them. The sound wave is produced at one focus and in photograph 24 it has almost reached the other focus. The expected symmetry of the direct and reflected waves at the center of the ellipse is shown nicely in photograph 22.

[1] P. Vieille, Comptes Rendus, 127, p. 41–43, 1898.

Photographs 25, 26, 27 and 28 show four positions of a sound wave reflected from and transmitted by a diffraction grating. The grating was made by cutting four equal and equally spaced rectangular slits (*O*, Fig. 5) in a strip of sheet tin 6 cm. wide and 18 cm. long. The slits were 7 mm. wide and 3.5 cm. long, with a strip of tin 7 mm. wide between the openings. The tin was tacked to a wooden block which served as a supporting base. The grating is placed with its apertures parallel with the spark gap. In this position the shadow on the photographic plate is edge on and the location of the apertures is not shown on the plate. To correct this fault pieces of heavy wire (*W*, Fig. 5) were soldered to the upper, lower and intermediate strips of tin, so that an edge on shadow of an aperture is narrow, of a reflecting surface it is broad.

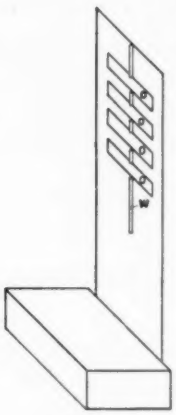


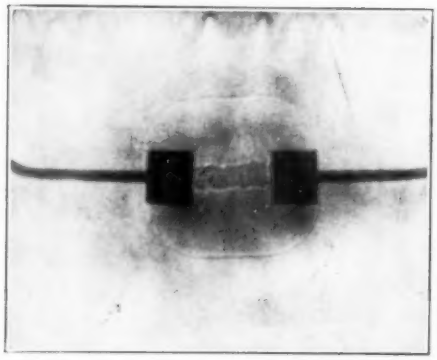
Fig. 5.

Both the reflected and transmitted system of waves are in complete accord with Huygens's principle. It seems to the writer that such photographs as these, or better, a chance to see the waves themselves, might be used by a teacher to give a concrete and definite idea of Huygens's principle and deductions from it, to students who have difficulty in forming mental images. Reality would be given to such terms as secondary waves, center of disturbance, pole of wave, wave front, common tangent, diffraction, etc.

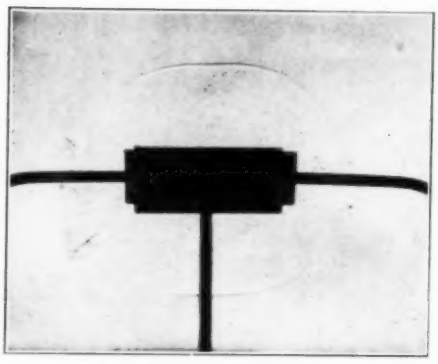
Photographs 29 and 30. These pictures were made by substituting a curved grating for the plane grating of the last four photographs. The grating is similar to the plane grating already described except that it has eight slits instead of four, and is cylindrical—having been curved over a piece of gas pipe. It was intended that the spark gap should be on the axis of the cylinder but it was accidentally displaced slightly before the photographs were taken. This explains why the transmitted and reflected wave systems are not symmetrical with respect to the grating and the spark gap.

All the photographs having a reflected wave show that a condensation is reflected as a condensation. This is true in the case of the hydrogen lens. While the film separating the rare hydrogen and the denser air is exceedingly thin, nevertheless it is a dense body so far as sound wave reflection is concerned. In a later paper the author will show waves reflected from the boundary between two gases of different density—when there is no film or other object separating them.

PHYSICS LABORATORY,
INDIANA UNIVERSITY,
June, 1912.



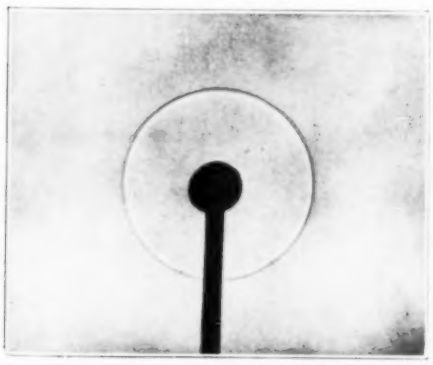
Photograph 1.



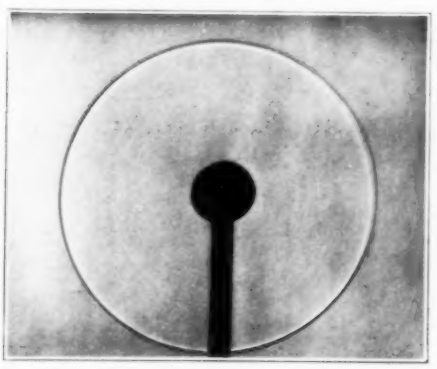
Photograph 2.

Photograph 3.

Photograph 4.

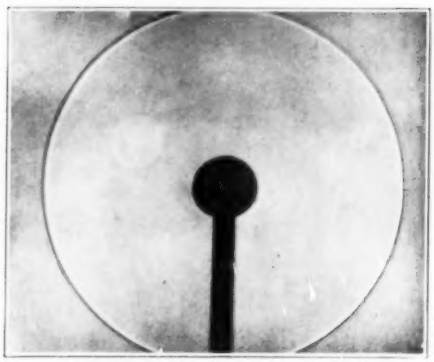


Photograph 5.

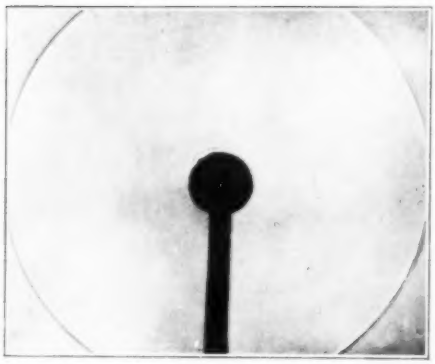


Photograph 6.

A. L. FOLEY AND W. H. SOUDER.



Photograph 7.



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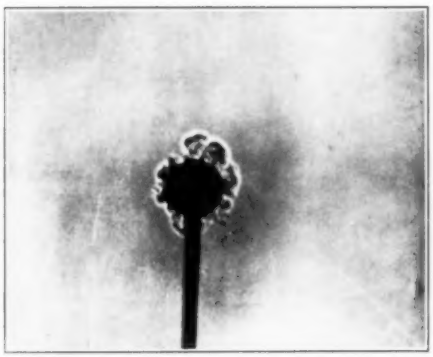

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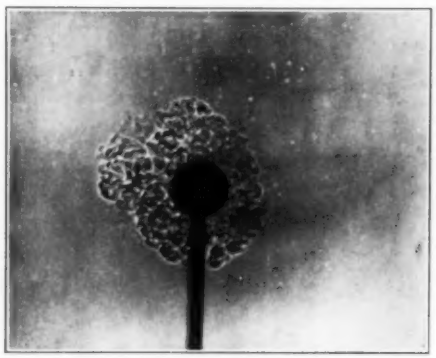

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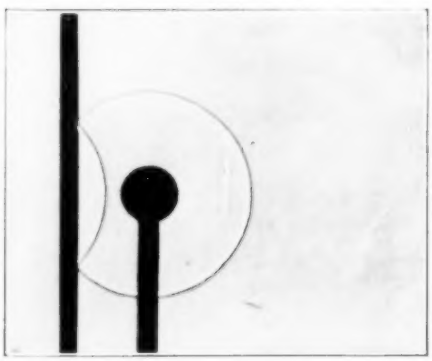

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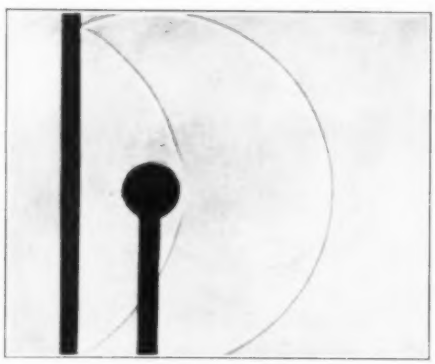
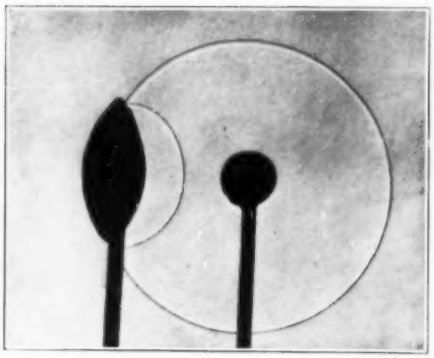


Photograph 12.

A. L. FOLEY AND W. H. SOUDER.

Photograph 13.



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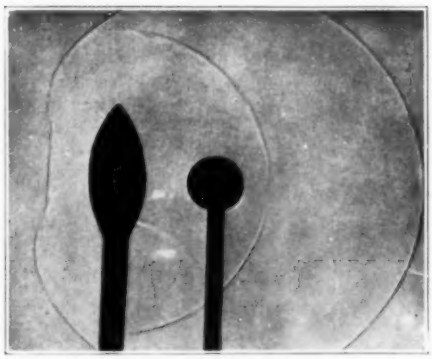

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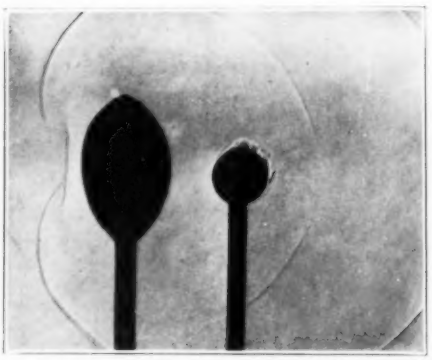

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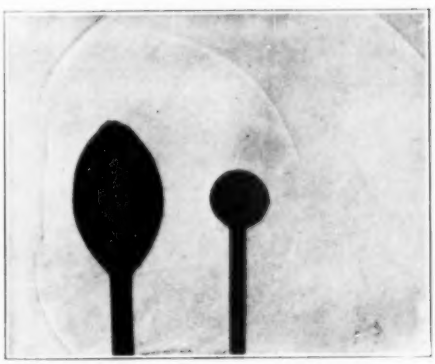

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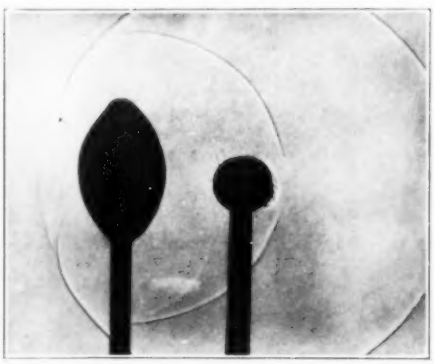

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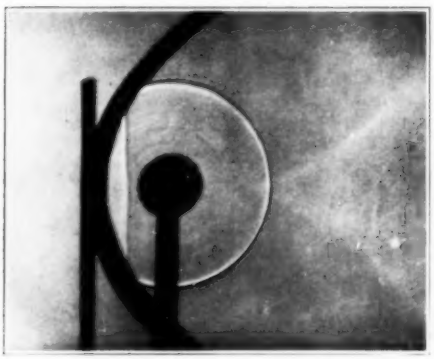

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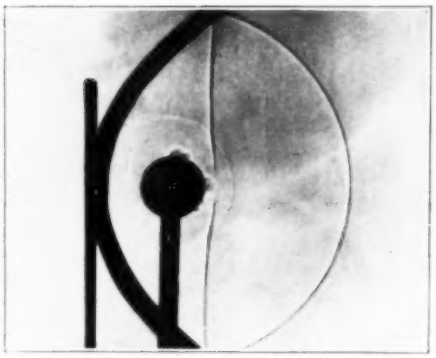

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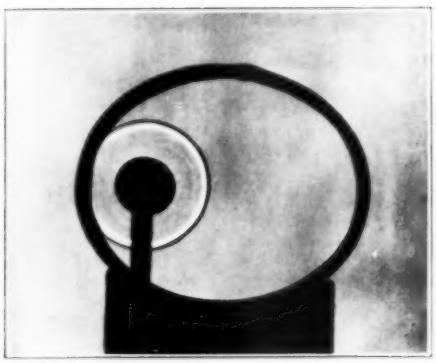

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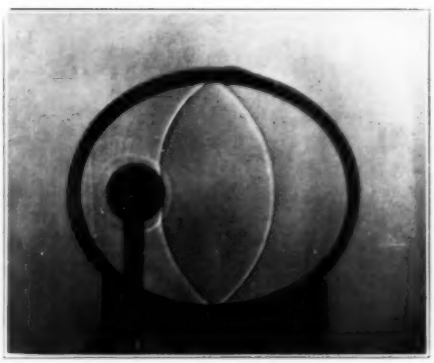

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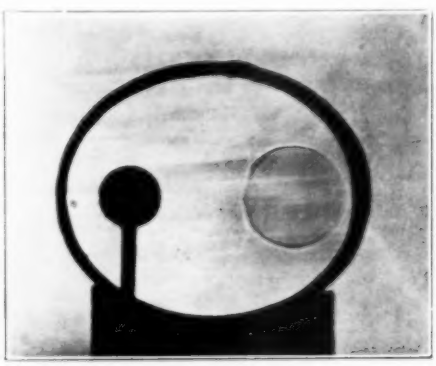

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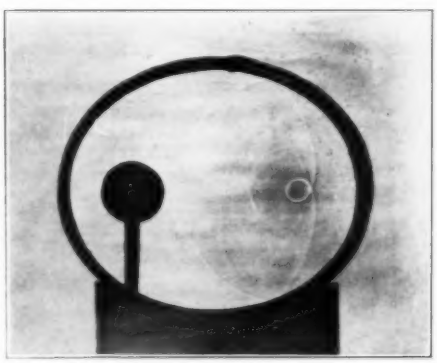

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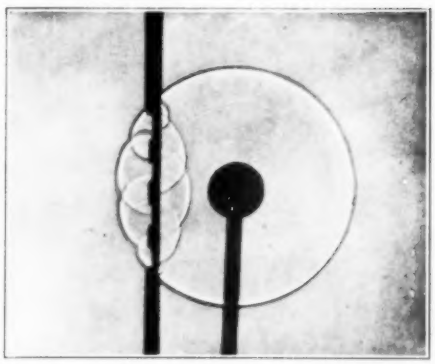

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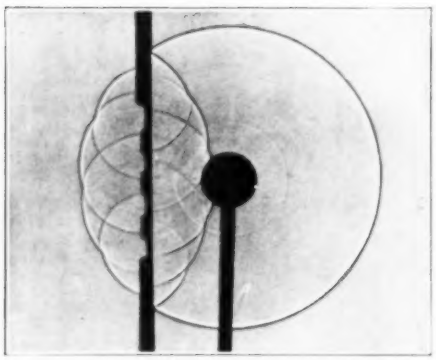

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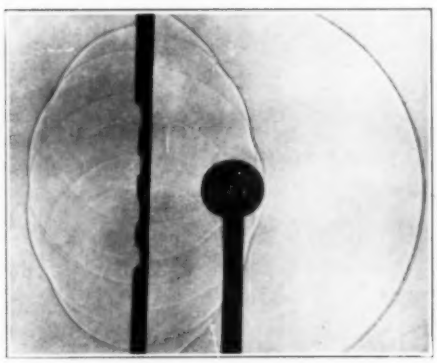

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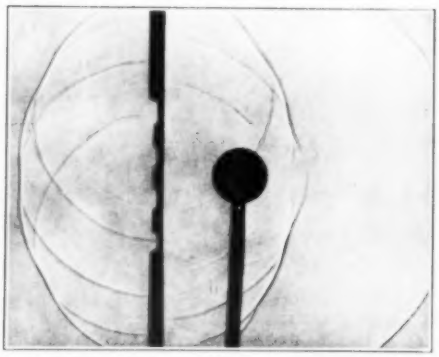

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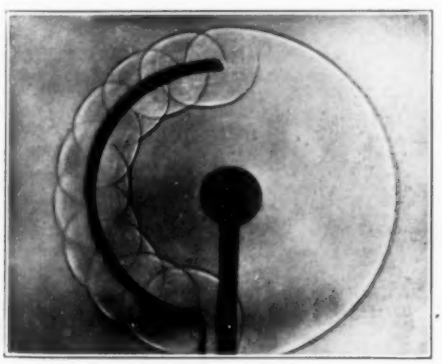

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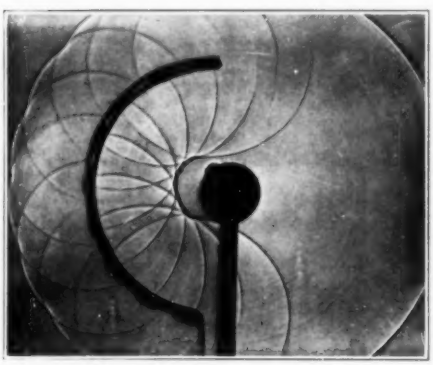

Photograph 30.

OSCILLOGRAPHIC STUDY OF THE SINGING ARC.

By J. E. Hoyt.

THE line of work taken up by the author in this paper was suggested by the remark of the editor of the London Electrician (Vol. 46, p. 356) in reference to the Duddell arc. "One feature of this experiment was brought out in this paper, viz., there is an alternate current generated by the arc of the same periodicity as the note emitted, but the experiment failed to make this clear. We would like to know if a telephone receiver placed in the circuit of the arc would emit a note that might be analyzed into only the same elements as the tone set up in the arc itself, or whether there are current variations set up other than those to which the shunt causes the arc to resound. In other words if Mr. Duddell's musical instrument were introduced into a telephone circuit, would the receivers in the circuit play the same tune as the arc itself, or would a jangle of other sounds be superposed upon the tune? Another question, if two or more arcs in series were to be separately shunted for different tones, would a telephone in series with all the arcs emit the chord combining the several tones?" No reports of work done along that line have come under this author's observation. Therefore it occurred to him that a qualitative study of the wave forms and of the harmonics present in the oscillations, and their relationships to the various conditions of the shunt circuit, of the arc itself and of the inductance in the source circuit, would be of interest. It was planned to make an oscillographic study of the resultant effect of two or more parallel circuits shunted about the arc, each with its own capacity and inductance, recording the current in the shunt circuits and in the arc at the same time.

The arc that was used in these experiments was an ordinary hand feed, vertical arc, capable of various adjustments, one of the electrodes being water cooled. The water furnished an atmosphere of vapor and produced stronger and more constant oscillations. Unless otherwise specified the electrodes were solid carbons 6–8 mm. in diameter. In the source circuit was usually connected as chokecoil, the primary of a transformer, and also a bank of incandescent lamps in parallel. The oscillograph was one of the G. E. type, having three bi-filar suspension systems. These were calibrated so that volts or amperes could be read directly from the curves. For the inductance of the shunt circuit there were two coils of

300 turns each of No. 10 wire, wound on cylinders 30.3 cm. in diameter and 93 cm. in length. The total resistance of one of these coils was about .9 ohm. The inductance was computed from Russell's formula,

$$L = (\pi dn)^2 l \left[1 - 0.424 \left(\frac{d}{l}\right) + 0.125 \left(\frac{d}{l}\right)^2 - 0.0156 \left(\frac{d}{l}\right)^4 \right],$$

and was found to be 6.82 $(10)^6$ cm. Connection could be made at various points so that the total induction of the coil could be varied by steps of 2.27 $(10)^5$ cm., and a bare wire coil could be connected in for finer adjustment. Three standard boxes of 10 mf. capacity each were used. Thus the lowest frequency calculated from Duddell's formula (which gives approximate values for low frequencies) would be 330 oscillations per second. For oscillographic study of course a low frequency was necessary. A preliminary investigation of the reliability of the stroboscopic and acoustic methods of determining the frequency of the electric oscillations was first decided upon. For the former a Duddell falling plate oscillograph was called into service using the singing arc itself as source of light. After overcoming very many difficulties a record was obtained which unfortunately is too faint for satisfactory reproduction. However, as might be expected, the spots of light evidently appear most distinct just after the minimum point of the potential difference curve, which corresponds to the instant after the maximum of the current. It is very evident, as was expected, that the variation in light intensity and current are isochronous.

In order to compare the electric and sound vibrations, it was decided to construct a sound oscillograph. This apparatus, as finally set up, consists of the following: Mounted on a heavy horizontal frame, attached to a heavy stand, is a heavy brass elbow, holding a brass frame about four inches in diameter, which in turn holds a fine specially prepared parchment diaphragm. The latter frame is so constructed that the tension of the diaphragm can be increased to the point of rupture. A high tension was used in this experiment. Also rigidly attached to the horizontal frame is a block, bearing on its face a flat section of a thick-walled brass cylinder. In this cylinder vertically opposite each other are two screws, in the ends of which jewel bearings are set, and between them is mounted the needle bearing the mirror. For this needle, the smallest that could be found anywhere was taken, cut in two and the blunt end sharpened. The mirror is about .03″ × .1″. The horizontal "suspension" is of unspun silk attached to the diaphragm at one end, passing around the needle, and attached at the other end to a very light spring, piece of spring brass, or even a very light rubber fiber. In order

to rotate the needle for adjustment of the mirror without changing the tension, the brass frame holding the needle was mounted on a brass platform. Two strips of spring steel held the frame against the block. Then by means of a screw at one side of the frame and a piece of spring steel at the other, the frame could be moved back and forth along the platform thus causing the fiber to rotate the needle without changing the tension. Two screws from the back of the block made it possible to tilt the frame, needle and mirror backward or forward as needed. Since the heat of the arc was much too great to bring near the diaphragm, it was necessary to make use of a parabolic reflector and parabolic megaphone to obtain sufficient energy at the diaphragm. However the acoustic apparatus responds to almost any noise in the room, and vibrates freely in response to the human voice or to a mounted tuning fork across the room.

In order to obtain simultaneous records a G. E. oscillograph was installed and a pencil of light from the third prism was intercepted with a right prism directing it through a hole in the side of the box, upon the acoustic system outside. From this mirror it was reflected back and onto the photographic film. The whole apparatus was connected up as in Fig. 1. The diagram of apparatus shows: *A.S.*, the arc source; *R.P.*, right prisms; *E.S.*, the electric oscillograph system; *A.O.S.*, the acoustic system; *P.M.*, the parabolic megaphone; *S.A.*, the singing arc; *P.R.*, the parabolic reflector. The connections for the singing arc show *S.A.*, the singing arc; *C.C.*, the choke coil; *S.R.*, series resistance in source circuit; *O*, the oscillograph loop; L_1, C_1 and O_1 represent the inductance, capacity and oscillograph loop for shunt number one; L_2, C_2 and O_2 have corresponding significance for shunt number two.

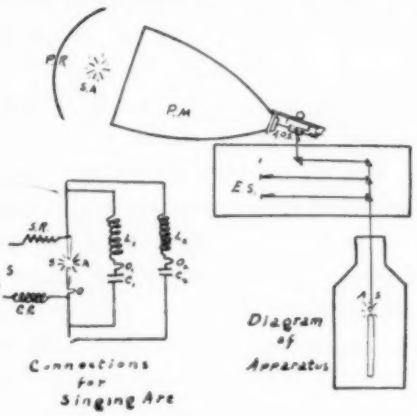

Fig. 1.

It was exceedingly difficult to obtain good records of the sound of the singing arc, for even while the arc is apparently constant as far as the ear could detect, yet the sound might be varying slightly in frequency. Even if the fundamental was constant, the harmonies due to conditions in the arc were changing in relative intensities and thus changing the character of the wave form. Still some very interesting records were

obtained, probably the first acoustic records of the singing arc, surely the first obtained simultaneously with the electric records.

Several preliminary records were made of the harmonic vibrations of several tuning forks, vibrating simultaneously. These records suggested a use to which the acoustic system may be devoted,—the obtaining of accurate time values for electric oscillations of low frequency. For example simultaneous records were made of the variation of the arc potential and the sound vibration of Sol_3 fork. Comparing the two it was found that the frequency of the arc was about 420 os./sec. Computation by the simple formula

$$n = \frac{1}{2\pi}\sqrt{\frac{1}{Lc}}$$

gave a value of approximately 430 os./sec. From this it would appear that the simple formula will do for rough approximations in the case of low frequencies, especially where the resistance is very small compared with the other quantities involved.

Fig. 2 is a record of the acoustic oscillations of the arc, the current through the arc and the current in the oscillating shunt. It is very evident that the fundamental of the sound has the frequency of both the arc and the shunt circuit. The latter is reversed in direction, but can be seen to be very nearly the complement of the variation in the arc current, although the current through the arc appears to be more nearly a sine function. A single harmonic appears in the sound vibration, which does not appear in the current curve. This is probably due to mechanical effects of the impact of discharge rather than the electrical conditions. The capacity and inductance of the shunt circuit were 10 mf. and $6.82\ (10)^6$ cm. respectively, giving an approximate frequency of 600. The maximum value of the current is a little over 3 amperes.

Some approximate measurements were taken of curves representing the variation of current through the arc and also the variation of sound.

Time in Sec.	Arc Current in Amp.	Relative Values from Sound Curve.
0.	−2.6	−32.
$1.6(10)^{-4}$	+3.0	−15.
$6.4(10)^{-4}$	+0.2	33.
$9.6(10)^{-4}$	−2.0	+ 5.
$14\ (10)^{-4}$	−3.1	−10.
$15\ (10)^{-4}$	−3.0	0.
$18\ (10)^{-4}$	−2.2	−10.
$22\ (10)^{-4}$	+2.2	−31.

Fig. 3 represents the arc potential, current in shunt and acoustic vibrations for two shunt circuits, natural frequencies, 210 and 420. The value of the inductance in the smaller shunt is half that in the larger, as well as the value of the capacity. The maximum value of the current which is here the combined current of the two shunts is about 5 amperes, the variation in potential difference about 72 volts. The harmonic in the latter is very pronounced here though the sound was that of the lower frequency, so far as the ear could distinguish; the record, however, evidently shows at least one harmonic present. The fundamental evidently is in phase with the current through the arc, opposite to that of the shunt, but, though the current through this shunt is far from a simple wave form it is impossible to ascribe the harmonics of the sound to variations in the current. Here the current was oscillating quite freely in both shunts but when the arc is responding to the higher frequency the lower frequency shunt is unaffected and the current in the combined shunt —the arc—approximates more nearly the sine form. Figs. 4 and 5 show curves for same quantities under different conditions. In cases where the natural frequencies of the shunts were related as 2–1, the arc was liable to see-saw up and down, now giving the higher tone, now the lower, but in general the higher tone was more stable at smaller distances between the carbons, while the lower tone was more stable with greater separations. Especially was this true where the relationship was not a simple one. The higher tone was obtained most clearly and was most stable when the separation of the arcs was only .04 inch, but the lower tone was most stable with a separation of .1 inch or more. This would seem to indicate a sort of tuning or resonance effect. It will be noticed in regard to the sound oscillations that the smoother and more sinuous the current curve, discharging through the arc, the simpler the sound oscillation. This might be explained on the idea of difference of impact in the arc.

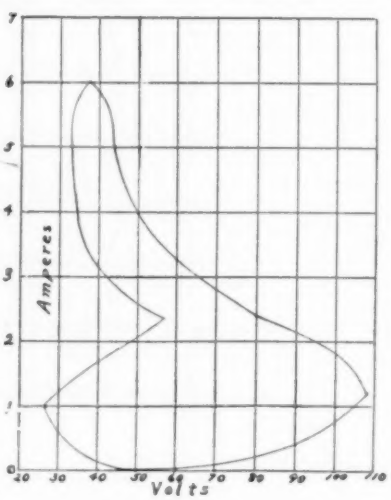

Fig. 6.
Dynamic characteristics. Pd. *vs.* current through arc.

Curves were also taken, showing the pd., current, and sound of arc, with no large inductance in the source circuit,—that is, with the choke coil removed. Two successive sets of curves were taken under the same

conditions, only in the second, the coil was again inserted but the two sets are almost identically alike in form. Blondel has noted a difference in the quality of the tone under these differing conditions, but as far as the acoustic record goes there is no considerable difference in wave form though there may have been some difference in period. Each was recorded with the first harmonic, only.

Fig. 6 is a curve showing the dynamic characteristics of the singing arc. This was obtained by projecting simultaneous curves of pd. and current and tracing on a screen. Simultaneous values were then obtained and

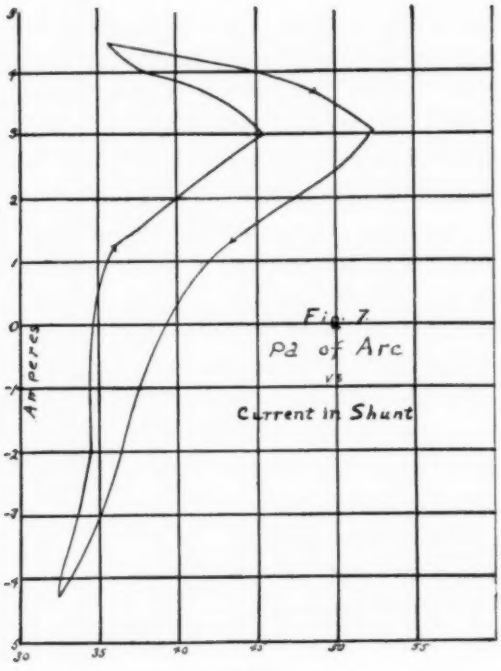

Fig. 7.

plotted. It can be seen that the current of the arc actually reaches o in this case. Then with slowly rising current the potential rises rapidly, reaching a maximum, then the current rises more rapidly as the potential falls. For a brief decrease of potential, the current falls rapidly, then the potential starts to increase to a second maximum, decrease, then increase until the current reaches o, when the cycle repeats itself. Thus for the greater part of the curve the dv/di is negative.

Fig. 7 represents the change of potential with variation of current in oscillating shunt. This, however, was with different constants in the

oscillating circuit, about 5.12 $(10)^6$ cm. inductance and 30 mf. capacity. It will be noticed that with increasing current and decreasing inverse discharge we have a slight increase of potential for a time, then a more rapid increase, then a rapid decrease of potential with increasing current. With decreasing current the potential increases to a second maximum, then decreases rapidly to a minimum value with maximum discharge of condensers through the arc.

Fig. 8 shows the currents through the arc, and through each of two parallel oscillating circuits. The circuits were arranged to give relative frequencies of 2/1, when the arc responded to them separately, but they

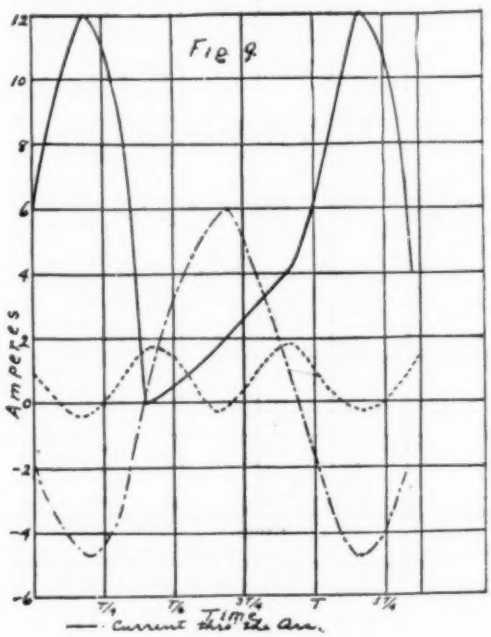

Fig. 9.

Solid line shows current through the arc; dotted line shows current through oscillatory shunt No. 1; broken line shows current through shunt No. 2.

simply produce a resultant effect regardless of the relative frequencies, generally oscillating with frequencies an octave apart. The discharge through the arc is far from a sine function, and the discharge through the oscillating circuit appears much more nearly a sine wave. Fig. 9 shows the relative values of these quantities; *i. e.*, currents in arc and shunt circuits, on a larger scale, drawn from a projection of a negative, on a screen. Apparently from this, the currents in the oscillating shunts are not quite sine functions, though more nearly so than the current through the arc. Apparently the current in the arc should equal the

sum of a constant d.c. and the sum of the discharges due to the shunt circuits. The current through the arc when not oscillating was about 7 amperes. The maximum value of the current in the arc is very nearly equal to the sum of the inverse discharges and this value. But in the neighborhood of its minimum value this does not hold true. Evidently the wave form would be affected by temperature of the carbons, ionization and inductance of the arc. The current is seen to rise very gradually at first then more suddenly as might be expected.

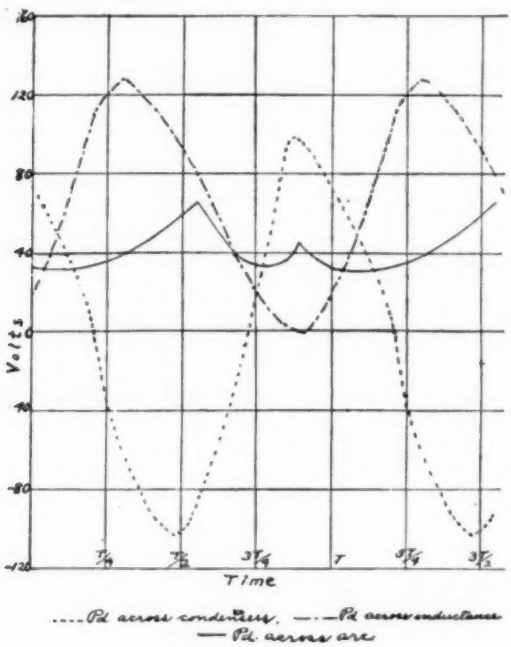

Fig. 11.

It was desired to find the relationship between the arc potential and the variation of potential differences at the terminals of the condenser and the coil in the single oscillating shunt. This is shown in Fig. 10. Fig. 11 shows a similar curve to a larger scale. The great variation in the pds. of the parts of the shunt contrast with that of the arc, the pd. variations of which bear little resemblance in amount or in phase with the individual variations or the vector sum of the pds. of condenser and inductance. It is quite evident that there must be something in the arc itself which influences the variation of potential, more than the conditions of the oscillating circuit. In general when the resulting potential of the shunt was rising the arc potential was falling and vice versa.

Fig. 12 shows the variations of potential across the arc, and across the condensers of the two oscillating circuits when the shunt circuits are tuned to the octave. Fig. 13 shows the same conditions as are represented

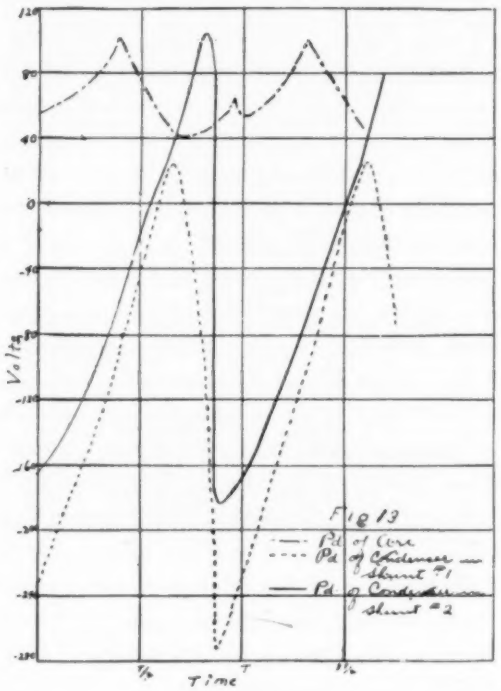

Fig. 13.

in Fig. 12, on a larger scale. The effect of adding another shunt was to produce a further relative phase shift. Furthermore the zero of these shunt curves is not the potential of the negative carbon, but about − 45 volts and − 120 volts respectively. It will be noticed through what a wide range the oscillations pass. The time of maximum current was not the same for each circuit and the rate of discharge was different, but the time for complete reverse discharge was about the same.

Summary.

Oscillograph curves are here reproduced from photographs, of varied electrical conditions of the singing arc. In the case of a single shunt the current in the arc is very nearly a sine curve and its frequency can be approximately determined from the simpler Duddell formula. The current through the arc is approximately that of the oscillating circuit superimposed upon the d.c. The effect of adding a second shunt is to cause the arc current to deviate largely from the sine form, nor does it

vary as the sum of the shunt inverse discharges. The current is evidently considerably affected by varying conditions in the arc. The arc potential does not even approximately follow the variation of the sum of the pds. of the condenser and inductance. The effect of introducing another shunt is to produce a phase shift in the condenser pds. which may have the same frequency of discharge even if of different natural frequencies.

An acoustic oscillograph was also constructed and herewith are reproduced the first acoustic curves taken of the singing arc, and possibly the first reproductions of simultaneous electrical and acoustic oscillations. Ordinarily for a single shunt it is found that the sound, which is isochronous with the electrical oscillations, is of a rather simple form, the oscillograms showing only a single harmonic. In the case where the arc current is more complex, as when two shunts are used, the resulting sound curve is quite complex. In the latter case the arc responds to one or the other of the shunt circuit frequencies, depending, *e. g.*, on the separation of the carbons. There seems therefore to be a sort of tuning effect, regulated by some electrical changes produced by opening or closing more or less the arc gap. This might possibly be explained by attributing the effect to the presence of induction in the arc, increasing with the separation. This inductive effect might also furnish the basis for an electrical explanation of the change of frequency with arc length which would be quite marked for higher frequencies where the inductance of the shunt is quite small. It is generally accepted that the singing arc discharge is rotational and that the pressure conditions in the arc are very peculiar.

No fundamental difference is recorded in the character of the sound oscillations for the two kinds of tones attributed to the oscillating discharge with and without inductance in the source circuit.

Considerable difficulty was early experienced in making the parts of the apparatus work together. Mechanical vibrations due either to the falling plate or the interaction of the motor and the oscillograph box to which the drum was attached, were hard to eliminate. The author is now designing an improved combined apparatus for the simultaneous recording of sound and electrical oscillations which he hopes to use for telephonic work, testing of diaphragms, etc.

In concluding, the thanks of the author are extended for the courtesy and suggestions of Professors Goodspeed and Richards, also for skilled assistance of Messrs. Jacob Martin and Kalmbach, in the construction of some of the apparatus.

RANDAL MORGAN LABORATORY,
UNIVERSITY OF PENNSYLVANIA,
June, 1911.

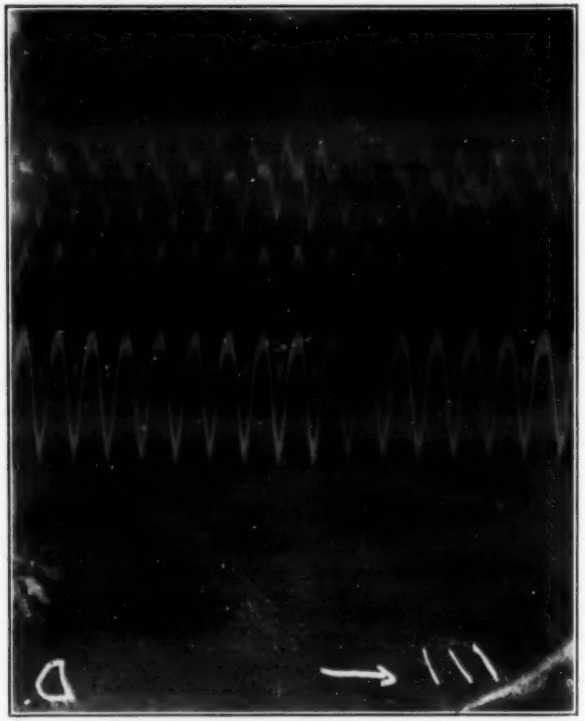

Fig. 2.

I_1 = current in shunt circuit; I_2 = current in arc circuit, A = mf.; L = 682 $(10)^4$ cm. acoustic oscillation; C = 10

Fig. 3.

E = pd. of arc; I_2 = shunt current; A = sound vibration; C_1 = 10 mf.; L_1 = 341 $(10)^4$cm.; C_2 = 20 mf.; L_2 = 682$(10)^4$ cm.

J. E. HOYT

Fig. 4.
$L_1 = 682\ (10)^4$ cm.; $C_1 = 10$ mf.; $L_2 = 170 + (10)^4$ cm.; $C_2 = 10$ mf.

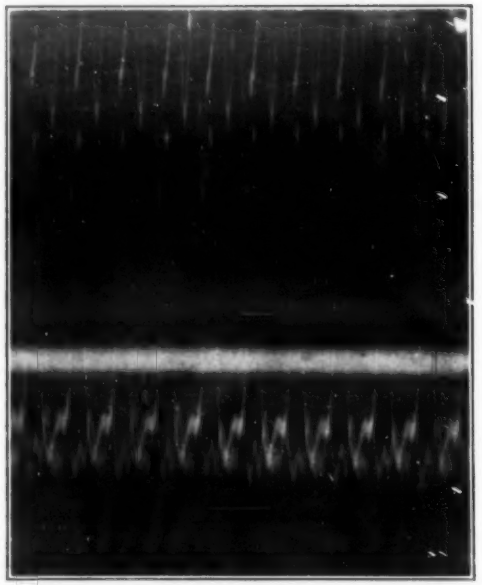

Fig. 5.
$C_3 = 20$ mf.; $L_1 = 682\ (10)^4$ cm.; $C_2 = 5$ mf.; $L_2 = 682\ (10)^4$ cm.

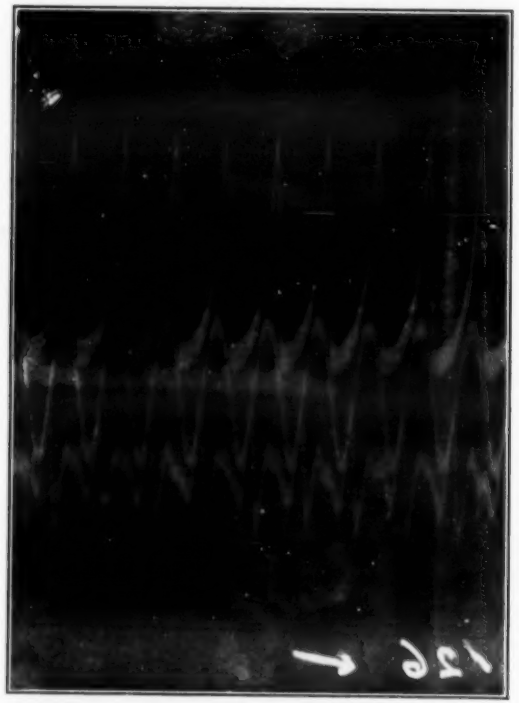

Fig. 5A.

I_1 = current in arc; I_2 = current in shunt; A = acoustic oscillation; $C_1 = 14$ mf.; $L_1 = 682\ (10)^3$ cm.; $C_2 = 14$ mf.; $L_2 = 170 + (10)^4$ cm.

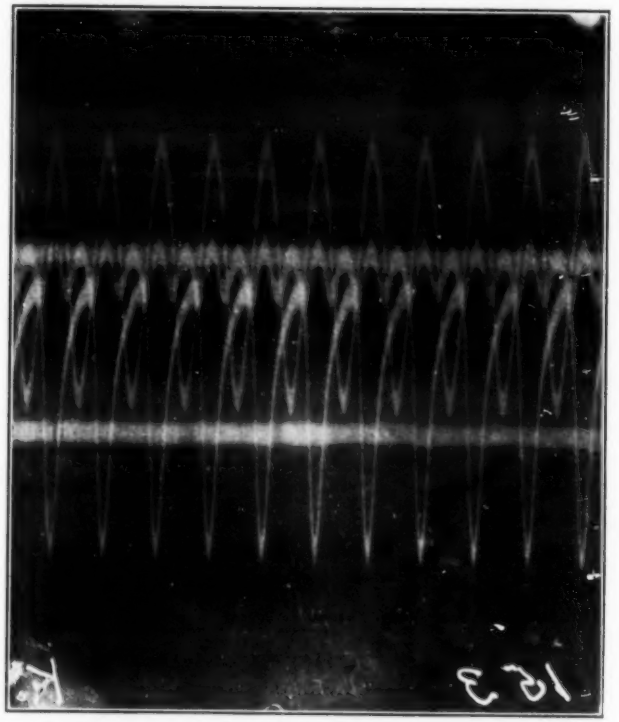

Fig. 8.

I = arc current; I_1 and I_2 = shunt currents; $C_1 = 30$ mf.; $L_1 = 682\ (10)^3$ cm.; $C_2 = 10$ mf.; $L_2 = 341\ (10)^4$ cm.

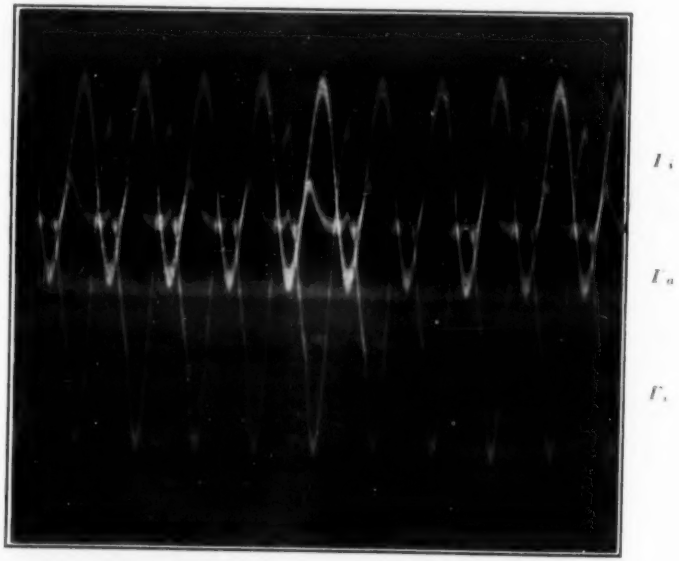

Fig. 10.

E_a = pd. of arc; E_c = pd. condenser; E_i = pd. of coil; C = 20 mf.; L = 682 $(10)^4$ cm.

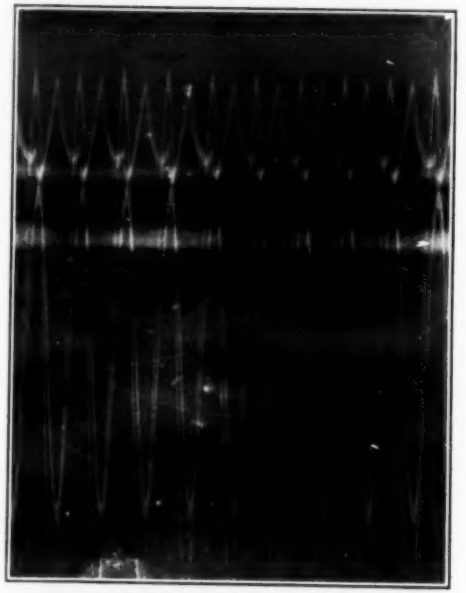

Fig. 12.

E_1, E_2 = pd. shunt condensers; E_a = pd. of arc; C_1 = 8 mf.; L_1 = 6 82 $(10)^4$ cm.; C_2 = 18 mf.; L_2 = 682 $(10)^4$ cm.

PROCEEDINGS

OF THE

AMERICAN PHYSICAL SOCIETY.

MINUTES OF THE SIXTY-THIRD MEETING.

A MEETING of the Physical Society was held in the Fayerweather Physical Laboratory of Columbia University, New York City, on Saturday, October 12, 1912. In the absence of the president and vice-president, Mr. Merritt was made temporary chairman.

The secretary reported to the meeting the result of the mail ballot which was held during May, 1912, in order to determine the sentiment of the members of the society in regard to the publication of a journal and the transfer of the control of the Physical Review to the Physical Society. This mail ballot was ordered by the council after the close of the Boston meeting, April 27, 1912, the council having adoped the suggestion contained in the following letter from the editors of the PHYSICAL REVIEW:

To the Members of the Council of the American Physical Society:

In March, 1911, the editors of the Physical Review submitted a statement to the Council of the Physical Society with reference to the transfer of the Review to the Society. (This statement will be found on page 593 of the Review for June, 1911.) Since that time the Society has had the matter under consideration and has requested the Council to prepare a plan for publishing a journal and to determine under what conditions the control of the Review may be transferred to the Society. The fact that the members of the Council are so widely separated has, however, made it impracticable to hold a well attended meeting of the Council to discuss the details of the proposed transfer. In order to avoid further delay the editors of the Review suggest that the question be submitted to the members of the Society for a mail vote, with the understanding that if the Society votes to assume control of the Review, the present editors and advisory editors shall constitute the editorial board for the first year, and that a detailed plan for the permanent conduct of the Review be submitted by this board for the approval of the Society within a year of the date of transfer. The advisory editors of the Review, whose names now appear on the front inside cover, are J. S. Ames, K. E. Guthe, J. C. McLennan, W. F. Magie, R. A. Millikan, E. F. Nichols, B. O. Peirce, C. A. Skinner, John Zeleny.

If the Society decides that this transfer is desirable and is ready to assume the responsibility for the maintenance of the Review under the conditions named a year ago, the editors of the Review are ready to make the transfer at the earliest date that is found practicable.

If, however, the Society does not reach such a conclusion and is not ready to assume such responsibility, the editors desire, on the first of January, 1913, to definitely adopt the plan of a representative editorial board to coöperate with the present editors. They will ask the present advisory editors to constitute such a board in the first instance and to assist the editors in perfecting a permanent plan of operation.

EDW. L. NICHOLS,
ERNEST MERRITT,
FREDERICK BEDELL.

February 22, 1912.

The secretary reported that ballots had been sent to all regular members, and that those who failed to vote at once received a second ballot and a communication from the secretary calling attention to the desirability of the vote being a large and representative one.

The total number of regular members entitled to vote was 316. 201 votes were cast. The five propositions submitted to the society are given below with the number of votes in favor of each proposition.

1. That no change be made in the relation of the Society with the Physical Review. 87 votes.

2. That on January 1, 1913, the Society take over the Physical Review under the conditions specified, and in the manner suggested, in the accompanying communication from the editors. 97 votes.

3. That the Society give up its connection with the Physical Review and undertake the publication of an independent journal. 16 votes.

4. That the Council of the American Physical Society be given full powers as the representative of the said Society to obtain a certificate of incorporation for the said Society under the laws of the state which shall be deemed by the Council most suitable. 129 votes.

5. That, if the Society votes to assume control of the Review, the present editors and advisory editors shall constitute the editorial board for the first year, and that this board shall be requested to prepare a detailed plan for the permanent conduct of the Review, to be submitted for the approval of the council and of the society within a year of the date of transfer. (The advisory editors of the Review, whose names now appear on the front inside cover, are J. S. Ames, K. E. Guthe, J. C. McLennan, W. F. Magie, R. A. Millikan, E. F. Nichols, B. O. Peirce, C. A. Skinner, John Zeleny.) 130 votes.

The secretary pointed out that the original proposition received from the editors of the Physical Review in March, 1911, called for the approval of a majority of the members of the society in order that the control of the Review and the responsibility for its maintenance should pass to the society. In

order that proposition 2 should carry, it would, therefore, have required the favorable votes of 159 members, whereas only 97 votes were received. The editors had raised no objection to the vote being taken of the regular members only, although they had intended that all members should have a voice in deciding a matter affecting all equally.

After some discussion of the financial aspects of the proposition for the society to undertake the publication of the Review, a motion was made and carried, requesting the Council to inquire into the practicability of obtaining the joint guarantee of a number of colleges, so as to make the financial position of the Society secure in case it should undertake such publication.

The following papers were presented:

The Reflection of Electrons. ALBERT W. HULL.

Theory of Contact Rectifiers. (By title.) LOUIS COHEN.

Variation of Electrical Resistance with Temperature. A. A. SOMERVILLE.

Analogue of the von Waltenhofen Phenomenon in the Joule and Wiedemann Magnetostrictive Effects in Nickel and Steel Rods. (By title.) S. R. WILLIAMS.

Conditions for Obtaining Rapid Light Fluctuations from Incandescent Wires. C. F. LORENZ.

Comparison of Small Electrostatic Capacities. J. C. HUBBARD and H. F. STIMSON.

The Spectral Luminosity Curve of the Average Eye. HERBERT E. IVES.

The Heat of Solution of Radium Emanation. (By title.) R. W. BOYLE.

Effect of Frequency on the Constants of an Oscillating Electrical System. J. C. HUBBARD.

The Asymmetric Emission of Secondary Radiation. O. W. RICHARDSON.

Equilibrium Figures. A. C. CREHORE.

The Intrinsic Brightness of the Glow Worm. HERBERT E. IVES.

Adjourned at 1 P.M.

ERNEST MERRITT,
Secretary.

ANALOGUE OF THE VON WALTENHOFEN PHENOMENON IN THE JOULE AND WIEDEMANN MAGNETOSTRICTIVE EFFECTS IN NICKEL AND STEEL RODS.[1]

BY S. R. WILLIAMS.

IT has been shown by Von Waltenhofen[2] that when a magnetic force is suddenly removed from an iron rod it leaves less residual magnetism than when gradually removed. A study has been made of the Joule and Wiedemann magnetostrictive effects in nickel and steel rods to see how these different magnetostrictive effects are influenced by a sudden or a gradual removal of the field previous to the magnetic force applied for giving the various magnetostrictive effects.

[1] Abstract of a paper presented at the New York meeting of the Physical Society, Oct. 12, 1912.

[2] Von Waltenhofen, Wien. Ber., 48, (2), p. 564, 1863; Pogg. Ann., Vol. 120, 1863.

The results show that the magnetostrictive effects are different when the previous field is removed suddenly than when decreased slowly. From the standpoint of the planetesimal hypothesis of magnetism this is in agreement with predictions and the results are of value in helping to form some idea of what happens when a piece of ferromagnetic substance is subjected to a magnetizing force.

PHYSICAL LABORATORY,
OBERLIN COLLEGE,
OBERLIN, OHIO.

THE REFLECTION OF ELECTRONS.[1]

BY A. W. HULL.

VON BAEYER found that when electrons moving with velocities greater than 1.6×10^8 cm./sec. fall on a polished metal plate, more than 60 per cent. of them are reflected, and it has been generally assumed that for slower electrons the amount of reflection would be still greater. I find, however, that for the slow electrons produced by ultraviolet light, in an enclosure devoid of electric force, the amount of reflection is extremely small, certainly less than 1 per cent.

Two plates, 4 cm. in diameter, were mounted parallel to each other in a glass tube. One, of aluminium, was connected to an electrometer and illuminated at its center by a very narrow, carefully diaphragmed beam of ultraviolet light. The other, of silver, was movable along the tube, so that its distance from the first plate could be varied from 4 mm. (in which position no light fell upon it) to 15 cm. The inside of the tube was lined with blackened copper gauze. The dimensions of the plates were such that when they were 4 mm. apart practically all the electrons shot off from the illuminated plate would strike the other; and if any were reflected they would all return to the illuminated plate, thus diminishing the total current from it. When the plates were 15 cm. apart none of the reflected electrons could reach the illuminated plate.

I found the current from the illuminated plate to be the same when the plates were 4 mm. apart as when they were 15 cm. apart (and for all intermediate positions of the second plate), showing no effect of reflection.

To avoid any complication due to contact difference of potential the whole cavity, including gauze and aluminium plate, was sputtered with a cathode deposit of silver from the silver plate, and the potential difference between all three was tested by the Kelvin capacity method and found to be less than .1 volt. The experiment was then repeated, with the same result.

More extensive experiments are now in progress to test the connection between these results and those of Von Baeyer.

WORCESTER POLYTECHNIC INSTITUTE.

[1] Abstract of a paper presented at the New York meeting of the Physical Society, Oct. 12, 1912.

Variation of Electrical Resistance with Temperature.[1]

By A. A. Somerville.

THE materials tested were in the form of powder. A porcelain tube was filled with powder and nickel terminals inserted into either end of the tube, by which terminals a slight pressure could be placed on the powder. The terminals were also used as leads from the unknown resistance to the wheatstone bridge.

The resistance of all the materials tested decreases with an increase of temperature. The resistance given is for a column of powder one centimeter in diameter and about three centimeters in length. Below is given the temperatures at which such materials tested measure 10,000,000 ohms. In most cases during heating, the material undergoes a chemical change, uniting with oxygen of the air.

	Degrees Centigrade.
CaO	465
ThO_2	700
U_3O_8	340
Sb_2O_3	470
Sb_2O_4	430
Ni_2O_3	300
SnO_2	270
$CuSO_4$	525
Fe_2SO_4	375
$NaCl$	300
Alberene	800

Uranium trioxide conducts slightly at room temperature but at a slight increase in temperature is changed to U_3O_8 which is a non-conductor at ordinary temperatures.

Antimony trioxide when heated to a temperature of about 600 degrees is changed to antimony tetroxide. At 700 degrees it melts.

Green nickel oxide is converted into nickel sesquioxide, Ni_2O_3 at about 120 degrees.

At about 865 degrees copper sulphate is decomposed into copper oxide and sulphur trioxide.

The iron sulphate decomposes at 730 degrees.

If a small amount of borax is added to zinc oxide there is a sharp break in the temperature-resistance curve at 615 degrees where the borax fuses.

At 700 degrees sodium chloride begins to decompose liberating chlorine and forming sodium oxide, Na_2O.

The Spectral Luminosity Curve of the Average Eye.[1]

By Herbert E. Ives.

PREVIOUS papers of this series[2] record an extended investigation of methods of heterochromatic photometry. As a consequence of this

[1] Abstract of a paper presented at the New York meeting of the Physical Society, Oct. 12, 1912.

[2] Physical Review, XXXII., p. 441; XXXIII., p. 561; XXXIV., p. 387; XXXIV., p. 389.

investigation a set of conditions for colored light photometry have been suggested for adoption, as follows:

1. The use of the flicker photometer.

2. An illumination of 25 meter candles.

3. A photometric field of 2° diameter surrounded by an approximately equally bright field of 25° diameter.

4. The use of a normal or average eye.

The fourth requirement demands a knowledge of the characteristics of the average eye. To meet this need spectral luminosity curves of eighteen observers have been determined by the method and conditions mentioned. The average value which may be considered as taken of a sufficiently large number of observers to be adopted as standard is given in the following table.

LUMINOSITY CURVE OF AN EQUAL ENERGY SPECTRUM.

Mean of Eighteen Observers.

.44μ	.029 [1]
.45	.047 [1]
.46	.073 [1]
.47	.107 [1]
.48	.154
.49	.253
.50	.363
.51	.596
.52	.794
.53	.912
.54	.977
.55	1.000
.56	.990
.57	.948
.58	.875
.59	.763
.60	.635
.61	.509
.62	.387
.63	.272
.64	.175
.65	.104
.66	.068 [1]
.67	.044 [1]
.68	.026 [1]

CONDITIONS FOR OBTAINING RAPID LIGHT FLUCTUATIONS FROM INCANDESCENT WIRES.[2]

BY C. F. LORENZ.

THE convenience and reliability of incandescent filaments compared with arcs and sparks make it worth while to consider under what conditions their use is practicable in cases when an illuminant is required which will re-

[1] Extrapolated.

[2] Abstract of a paper presented at the New York meeting of the Physical Society, Oct. 12, 1912.

produce as light fluctuations any fluctuations in the electrical energy supplied to it. Compared with the spark the frequencies at which such filaments may be operated will of course be low.

Since the factor which retards and smooths out the temperature fluctuations is the thermal capacity of the filament, the first step toward making such an illuminant useful as a source of light for stroboscopic work is to choose the diameter of the filament as small as possible, since reducing the diameter reduces the thermal capacity in a greater ratio than the radiation. Assuming that the diameter has been reduced as far as practicable the following methods of further increasing the stroboscopic effectiveness suggest themselves: Running the filament at excessive temperature to increase the rate of cooling; using a color screen to limit the transmitted light to the shorter wave lengths, for which the fluctuation is greater than for the longer wave lengths; operating the filament in a cooling gas. Experiment shows that of these the last is by far the most effective. The ratio of the energy abstracted by the gas to the energy radiated, although not great for comparatively large wires (say of the order of 1 mm.) when they are at high temperatures, becomes very great for very fine filaments. The method involves a large waste of energy, but this may in some cases be of no moment, as for example in the measurement of alternating current frequency.

When operated with alternating current of any ordinary frequency a very fine filament lamp, say a 10 watt, 110 volt, tungsten lamp, gives only a very blurred stroboscopic effect, whereas even a larger filament, say one from a 25 watt, 110 volt, tungsten lamp, when mounted in an atmosphere of ammonia gives an effect amply sharp for frequency measurement of such currents. While the energy fluctuation is approximately a sine-squared function of the time, the light fluctuation is much more abrupt, the light being quite discontinuous, which is of course explained by the fact that the light emitted by a body varies much more rapidly than its temperature. In ordinary vacuum incandescent lamps on the other hand, the light fluctuations under alternating current operation are pretty closely sinusoidal. If, instead of the sinusoidal alternating current we use an intermittent current having energy concentrated in sharp pulses, the stroboscopic sharpness obtainable from the wire operated in a gas is much increased.

The Asymmetric Emission of Secondary Rays.[1]

By O. W. Richardson.

THE fact of the emission of more secondary radiation from thin plates in the emergent than in the incident direction is now well established in a number of different cases. The existence of these effects has been taken to indicate that the primary rays are either material (Bragg) or at least have a discontinuous or atomic structure. Since the effect is shown by light, the latter view, which has been advocated on these or other grounds by Sir. J. J. Thomson,

[1] Abstract of a paper presented at the New York meeting of the Physical Society, Oct. 12, 1912.

Stark and other writers, has probably received more favor. The object of the present paper is to see if an estimate of the maximum effects to be observed may not be obtained without making any definite hypothesis about the structure of the radiation. So far as the author is aware there are no facts known at present which definitely exclude the possibility of an explanation of these effects on the basis of the usual continuous electromagnetic theory of light and X radiations. The paper is practically confined to the case in which the secondary radiation consists of emitted electrons.

It is assumed that the action between the radiation and the matter is primarily one between radiation and electrons, and that this action, in the case of any particular electron, is a continuous one until disruption occurs. The act of disruption terminates the continuity of the preceding processes and is succeeded by a new cycle of similar events. In general disruption only involves the breaking up of a previously existing dynamical system, but in favorable cases it may result in electronic emission. The condition for disruption in the cases considered is that the energy of an electron should be equal to $h\nu$, where ν is the frequency of the radiation and $h = 6.55 \times 10^{-27}$ erg sec. An estimate of the maximum degree of asymmetry to be found in the most favorable cases is obtained by assuming that up to the instant of disruption, no part, either of the energy or of the momentum, which any particular electron receives from the radiation, is communicated to the rest of the matter.

Consider the case of X radiation or light incident normally on a thin plate of absorbing matter. In the steady state it follows from the principle of the conservation of energy that the energy lost by the radiation in any interval is exactly equal to the energy $Nh\nu$, at the instant of disruption, of the N electrons disrupted during that interval. And further, if the principle of the conservation of momentum is applied to the whole system of matter and radiation, the momentum lost by the radiation is equal under the same conditions to the sum of the momenta of the N disrupted electrons. If $\bar{u}$ is the average velocity of them in the direction of the primary radiation, m their mass, and λ the momentum lost by the incident radiation when it loses unit energy, then

$$\bar{u} = \frac{\lambda h\nu}{m} = \frac{\lambda}{2} v^2, \tag{1}$$

where v^2 is the mean square of their velocity at the instant of disruption. On the electromagnetic theory $\lambda = 1/c$ and

$$\bar{u} = \frac{h\nu}{cm} = \frac{v^2}{2c}. \tag{2}$$

These relations are not sufficient to determine the distribution of velocity among the particles. But the asymmetry should be more marked the greater $\bar{u}/v$ and hence the greater the value of v. Thus those radiations which give rise to the emission of electrons with the greatest velocities should exhibit the greatest degree of asymmetry in this emission. This is known to be the case. As an illustration the limiting value $\bar{u}/v = \frac{1}{2}$ for $v = c$, the velocity of light, is considered.

Fig. 2.

Fig. 3.

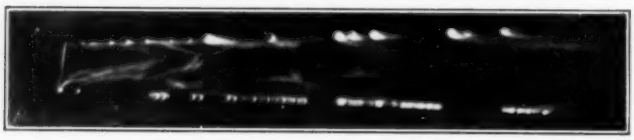

Fig. 4.

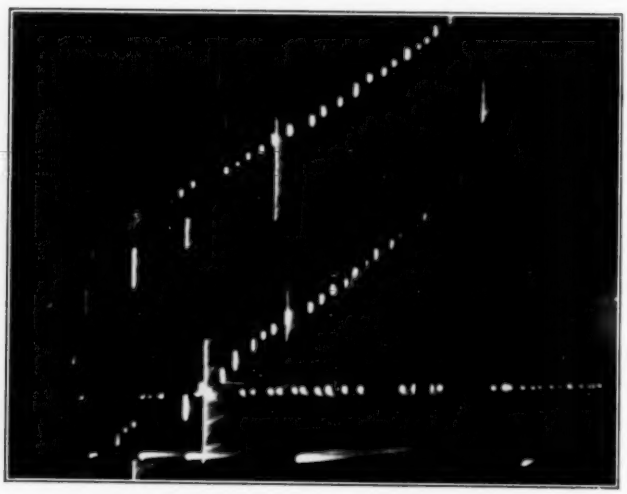

Fig. 5.

R. R. RAMSEY.

In the neighborhood of $\nu = 10^{15}\,\text{sec}^{-1}$, u/v from (2) is only about 1/500. The asymmetry found by Stuhlmann with ultraviolet light seems greater than this value of $\bar{u}/v$ would lead us to expect. However, the case of ultraviolet light is different from that of the other radiations, since we are near the limiting value of ν below which no emission occurs. A small asymmetry is shown to be equivalent to a proportional change in the length of the effective spectrum and thus to produce a magnification of the effect. Under certain circumstances the experimentally observed asymmetry should be greater with the more electro-negative elements. There is some evidence in favor of this in the experimental results.

In the case of the asymmetric emission of radiation of the X type also, the explanation offered by the electromagnetic theory, along the line considered by Sommerfeld, is still one which has to be reckoned with.

PALMER PHYSICAL LABORATORY,
PRINCETON, N. J.

THE OSCILLATORY DISCHARGE OF A LEYDEN JAR.[1]

BY R. R. RAMSEY.

WHILE setting up the apparatus to show the oscillatory discharge of a Leyden jar by the revolving mirror method I noticed that the mirror fanned the spark to one side of the terminals of the spark gap and thus spread the discharge. The thought occurred to me that an air blast might be used to show the oscillation. Two iron rods were placed one above the other in a wooden support, the divergence from parallelism being very slight and the distance at the closer end being approximately one centimeter. A blast of air was directed against the vertex of the triangle thus formed. These rods were then made the spark gap of the oscillatory circuit. The discharge which originates between the rods at the closest point follows the ionized air as it is carried horizontally by the air current. Thus the spark is spread over a space of five or ten centimeters. When the condenser consists of five or six ordinary leyden jars and is charged by a medium-sized glass plate machine the discharge takes place once every five or ten seconds.

As a lecture experiment this has the advantage over the revolving mirror method in that every discharge is visible to every member of the class irrespective of his position in the room. In looking up the literature on the subject I find that this method has been used by L. Zender (Ann. der Phys., 314, 1902, p. 899) and by G. A. Hemsalech (Compt. Rend., 140, 1905, p. 1103). They give photographs of the discharge but the detail of the discharge is lost in the photograph due to the fact that several discharges are superimposed upon the plate.

The discharge was so beautiful that it was thought worth while to photograph it. In order to increase the brightness of the spark the terminals were

[1] Abstract of a paper presented at the Chicago meeting of the Physical Society, December 2, 1911.

made of magnesium ribbon mounted between wooden strips, Fig. 1. By this means a single discharge made a good impression on the plate.

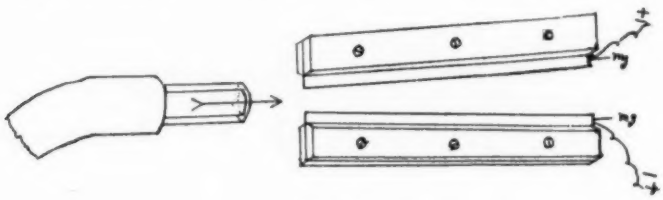

Fig. 1.

Fig. 2 shows the discharge when the capacity, C, is .012 M.F. and the inductance, L, is 65 henrys.

Fig. 3, $C = .025$ M.F. and $L = 65$ henrys.

Fig. 4, $C = .05$ M.F. and $L = 65$ henrys.

As the capacity is increased the discharge takes on more of the character of a flame and the detail of the discharge between the terminals is lost, but the discharge points on the terminals become more luminous, as is shown in Fig. 4.

In order to show better the character of the discharge a sensitive film was wound around an eight-inch motor pulley and placed so that the focal plane of the camera was tangent to the film.

Fig. 5 shows a horizontal line of discharge taken when the motor was not running, and two lines of discharge at about 45 degrees taken, when the motor was running at 1,200 R.P.M.

This shows that each oscillation occurs at regular intervals along the terminal.

The inductance used was the secondary of an eight-inch induction coil of 12,000 ohms resistance and an inductance measured by means of a standard inductance and a sechometer of 65 henrys without the iron core in place and 140 henrys with the iron in the core. The capacity was a variable glass plate condenser imbeded in paraffin. The values given are those obtained by ordinary laboratory methods.

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